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NO. 120

# UNIVERSITY OF ILLINOIS BULLETIN

Vol. XVIII

ISSUED WEEKLY

March 21, 1921

No. 29

[Entered as second-class matter December 11, 1912, at the post office at Urbana, Illinois, under the Act of August 24, 1912. Acceptance for mailing at the special rate of postage provided for in section 1103, Act of October 3, 1917, authorized July 31, 1918]

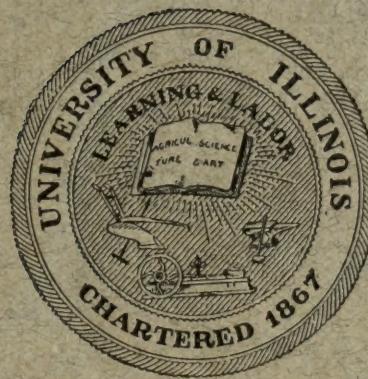
## INVESTIGATION OF WARM-AIR FURNACES AND HEATING SYSTEMS

BY

A. C. WILLARD

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[THIS BULLETIN IS THE THIRD OF A SERIES ON WARM-AIR  
FURNACE RESEARCH]

BULLETIN No. 120

ENGINEERING EXPERIMENT STATION

PUBLISHED BY THE UNIVERSITY OF ILLINOIS, URBANA

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PRICE: SEVENTY-FIVE CENTS

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MARCH, 1921

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INVESTIGATION OF WARM-AIR  
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CONDUCTED BY  
THE ENGINEERING EXPERIMENT STATION  
UNIVERSITY OF ILLINOIS

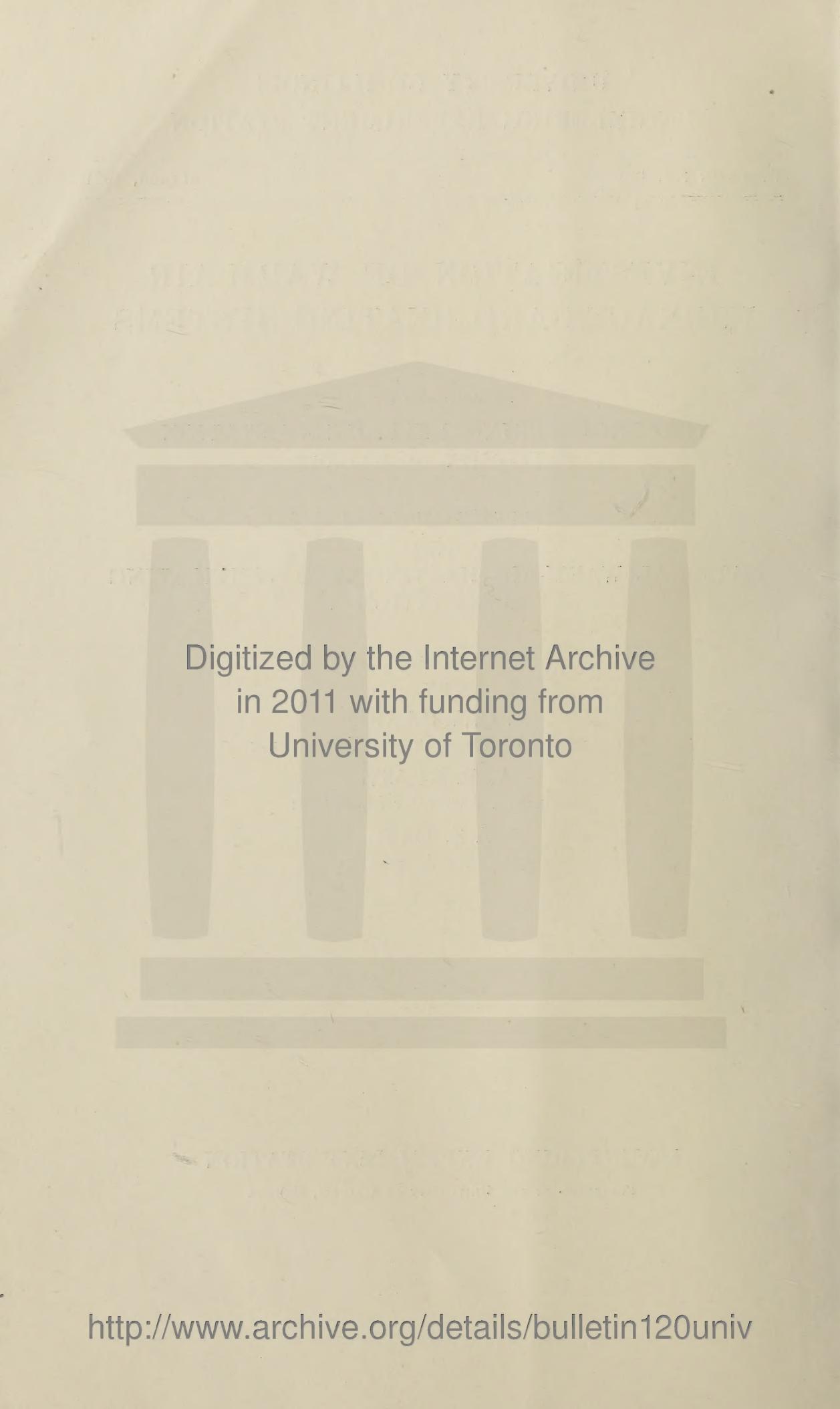
IN COÖOPERATION WITH  
THE  
NATIONAL WARM-AIR HEATING AND VENTILATING  
ASSOCIATION

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ENGINEERING EXPERIMENT STATION

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# INVESTIGATION OF WARM-AIR FURNACES AND HEATING SYSTEMS

## I. GENERAL STATEMENT CONCERNING THE INVESTIGATION

1. *The Coöperative Agreement.*—This Bulletin is the second report of progress under the present coöperative agreement\* between the National Warm-Air Heating and Ventilating Association and the University of Illinois for an investigation of warm-air furnaces and furnace heating systems. The agreement was formally approved in August 1918, and the research work began in October of that year. A first "Report of Progress in Warm-Air Furnace Research," Bulletin No. 112 of the Engineering Experiment Station, has already been issued and was presented to the Association at its annual meeting in Columbus, Ohio, on June 11, 1919. A special bulletin, "The Emissivity of Heat from Various Surfaces," Bulletin No. 117 of the Engineering Experiment Station, was presented to the Association at its annual meeting in Cleveland, Ohio, on April 21, 1920. In addition to these, two special reports have been made to the American Society of Heating and Ventilating Engineers on the subjects of warm-air furnace testing.†

The present bulletin deals principally with the work accomplished since April, 1920, but in addition to this reference has been made to material contained in the earlier bulletins, and some of the more important results of the earlier work have been repeated in this bulletin. In such cases references to the previous bulletins are clearly indicated.

2. *Objects of the Investigation.*—The principal objects of the investigation are briefly stated as follows:

- (1) To determine the efficiency and capacity of commercial warm-air furnaces under conditions similar to those existing in

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\* See "Report of Progress in Warm-Air Furnace Research." Univ. of Ill. Eng. Exp. Sta., Bul. 112, Appendix II, pp. 61-63, 1919.

† "A Report of Progress in Warm-Air Furnace Testing at the University of Illinois," Journal of American Society of Heating and Ventilating Engineers, Vol. 26, No. 2, March, 1920.

"Proposed Furnace Testing Codes for both Pipeless and Piped Furnace Systems, as Developed in the Warm-Air Furnace Research Work at the University of Illinois," Journal of American Society of Heating and Ventilating Engineers, Vol. 27, No. 2, March, 1921.

actual installations, with leaders, stacks, and registers, to form a complete system.

(2) To determine satisfactory and simple methods for rating furnaces so that the proper size and type of furnace can be definitely selected for the service required.

(3) To determine methods of increasing the efficiency and capacity of furnace heating equipment, and the advantages or desirability of certain types of design.

(4) To determine the heat losses in furnace heating systems and the value of insulating materials as affecting the economy of the furnace, or the leaders and stacks, and finally of the system as a whole.

(5) To determine the proper sizes and proportions of leaders, stacks, and registers supplying air to first, second, and third floors.

(6) To determine the friction losses in cold air or recirculating ducts and registers, and their proper size, proportions, and arrangement or location.

(7) Eventually, to make a study and comparison of outside and inside air circulation as affecting the economy and operation of furnace systems.

In addition to these, the original objects of the investigation, there has been added the investigation of ordinary gravity type furnaces operating with small motor driven fan units. Such units are not intended for continuous service, but will merely serve to accelerate the air flow in cold weather, and temporarily to increase the capacity of a gravity system. It should be made clear that this work with small fan units does not include, at present, the more elaborate "fan-furnace" systems which are installed in large buildings to provide for both heating and ventilation.

3. *Discussion of the Problem and Methods Employed.*—It should be noted at the outset of this discussion that the fundamental ideas involved in the methods used in this investigation, as well as the furnace plant itself and its essential features, were developed and put into operation by the Department of Mechanical Engineering of the University of Illinois in the spring of 1918. This preliminary work soon developed the fact that very little could be accomplished in

the investigation of warm-air furnaces and furnace systems unless the furnaces were operated under the natural gravity flow conditions which exist in the actual installations. The research aspects of the problem then became very definite, and may briefly be stated under two general heads:

1. The exact measurement of large quantities of air, flowing at very low velocities, under extremely small heads, but at atmospheric pressure, and usually at high temperature; this measurement, moreover, must be made just as the air enters or leaves a register face, and, in piped furnace work, at a number of widely separated register faces.
2. The exact measurement of the temperature of air flowing over hot metallic surfaces, at points where the temperature measuring element is in fairly close proximity to the hot surface; this case, also, requires additional temperature readings to be taken simultaneously at many points.

These two problems have occupied the research staff almost constantly since the work began. The first problem has been solved by an indirect method, using anemometers and an elaborate calibrating plant. The second problem has been solved by the use of thermo-couples and a potentiometer, after calibrating all couples in position, and determining the correction for radiation for each couple exposed to hot surfaces.

## II. SUMMARY OF PRINCIPAL RESULTS TO DATE

4. *General Classification of Results.*—Any discussion of the results so far obtained by the furnace research staff can be divided naturally into two parts, the first dealing with the special apparatus and methods that have been developed for doing the testing work, and the second with the actual performance data obtained from the tests which have been made on various kinds of furnace equipment.

5. *Special Apparatus and Methods.*—The measurement of air velocity and the temperature of air under the particular conditions existing in warm-air furnace heating by natural circulation has required the erection of full-size plants operating under actual conditions and the development of special testing equipment and methods which are briefly outlined in the following paragraphs. The itemized list of results here given will also serve as a general index in finding most of the information given in the bulletin.

(1) A complete three story furnace heating plant with 10 leaders, stacks, and registers operating by natural circulation on recirculated air has been erected and is now in operation. (Section III.)

(2) A complete pipeless furnace plant of the single register type also operating by natural circulation on recirculated air has been erected and is now in operation. (Section IV.)

(3) Methods of operating these plants under uniform conditions, using any solid fuel, so that reliable test data may be secured, have been developed and perfected. This includes special temperature regulating devices operating by automatic draft control, which have been found of prime importance in this work. (Section V and VI.)

(4) A satisfactory method of making accurate measurements of air temperatures in close proximity to hot furnace castings has finally been perfected. This involved the determination of the radiation effect of such castings on small thermocouples, the measurement of the castings temperature and the development of an air temperature-rise indicator of great sensitiveness. (Section VI.)

(5) Methods for measuring the true amount of air issuing from register faces at low velocity have been perfected for both piped and pipeless furnaces. Similar methods have been developed for checking the amount of air entering a furnace at the same time. (Section IX.)

(6) A positive and fundamental method of calibrating all air measuring instruments used in this work against *weight of air*, with an accuracy well within one per cent, has been developed, and is always available. (Sections VII and VIII.)

(7) A special manometer reading directly to 0.001 of an inch head of alcohol has been developed and four of these gages are now in use. (Section IX.)

6. *Performance Data and Results Obtained from Tests.*—The tests so far run have covered a wide range, and include not only tests on the main plants, but also tests on much of the auxiliary equipment used in furnace heating.

(1) Complete testing codes for both piped and pipeless furnaces have been drawn up, tried out in detail, and are now before the American Society of Heating and Ventilating Engineers. (Section V.)

(2) The measurement of air temperatures across an air stream such as that flowing in furnace leaders or stacks has been made, and the differences between the air and the pipe temperatures accurately determined. (Section VI.)

(3) The heat loss from a pipeless furnace has been determined. (Section X.)

(4) The heat insulating efficiency of most of the commercial furnace pipe and casing coverings has been measured. (Section XI.)

(5) The investigation of the relative value of solid and slotted fire pots has been begun and results with furnaces operating on hard and soft coal obtained. (Section XII.)

(6) The application of small fan units to ordinary furnace installations has been made one of the objects of the investigation and the results of the preliminary investigation are included in this report. (Section XIII.)

(7) A study of the proper proportions for leaders and stacks has been made, and the air carrying capacities of leaders and stacks with varying relations of cross sectional area have been ascertained. (Section XIII.)

(8) The effect of one type of register grille on the air delivering capacity of a pipeless furnace has been determined. The study of register grilles in general is now in progress. (Section XIII.)

(9) The effect of height of register above the furnace, and the air temperature at the register, on furnace or leader capacity has also been determined for the piped furnace. (Section III.)

(10) Typical performance curves for both piped and pipeless furnaces, showing the relation between combustion rate, draft, heating capacity, air temperature at registers, and efficiency, have been obtained. (Sections III and IV.)

(11) Comparative tests of a pipeless furnace operating first on hard coal and then on soft coal have been made, but complete performance curves on soft coal are not yet available. (Section IV.)



FIG. 1. THE MAIN PLANT, FRONT VIEW

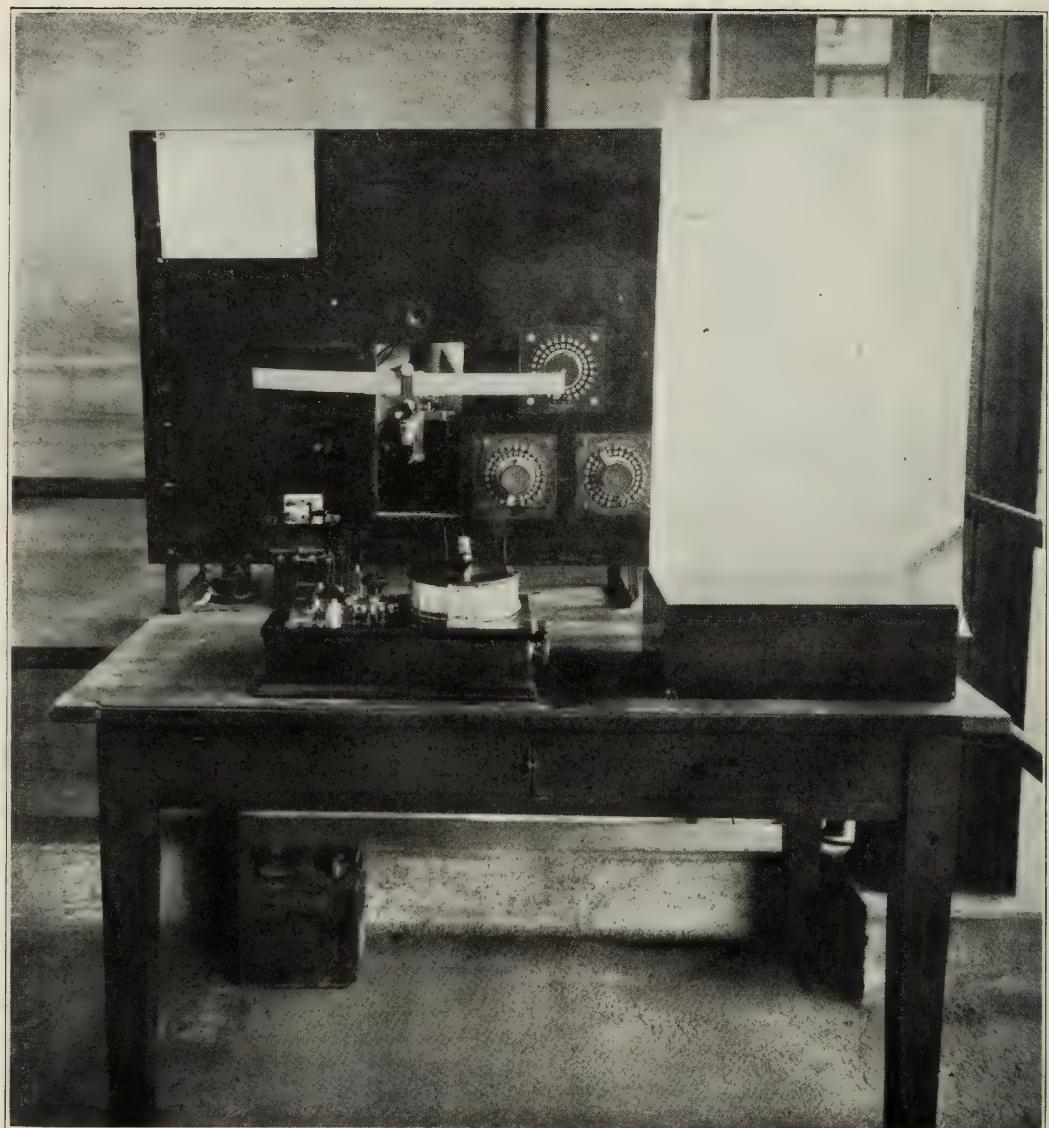


FIG. 2. SWITCHBOARD AND INSTRUMENTS

### III. THE PIPED FURNACE PLANT

7. *General Description of Plant.*—A general view of this plant is shown in Fig. 1. A comparison of this figure with Fig. 1 of the previous report\* of progress will show the following modifications in the equipment. For sectional elevation and plan of this plant see Figs. 3 and 4.

(a) The main switch board and the instruments (Fig. 2) for reading temperatures have been moved from the first floor of the plant (Fig. 3) to the main floor of the laboratory. (See Fig. 1 at right hand lower corner.) This change gives a much steadier mounting for the instruments, and also makes it possible to use the switch board for temperature readings on the other two plants as well as on the piped furnace plant.

(b) A special closed calorimeter tank, a, (Fig. 5) of the same diameter as the furnace and one inch high has been placed under the furnace for determining the radiation loss from the fuel bed or fire-pot to the floor. This tank is supplied with water which intercepts the radiant heat that would otherwise enter the floor, and thus makes it possible to determine the magnitude of the loss to the floor.

(c) An open calorimeter tank, b, has been placed on top of the furnace bonnet (Fig. 5) for determining the radiation loss from the top of the bonnet. This tank is supplied with water and functions in much the same way as the bottom tank.

(d) A black iron adjustable shield, c, (Fig. 5) has been placed just inside the furnace casing so that it reaches from grate level to under side of radiator. Its position can be changed, by long screws, in order to increase or diminish the distance between this shield and the casing. This shield acts as secondary heating surface, since it intercepts the radiant heat from the fire-pot and combustion chamber so that this heat may be transferred to the air passing up through the furnace.

(e) Two horizontal curved shields, d, of black iron (Fig. 5) have been inserted in the recirculating duct at the point where this

\* "Report of Progress in Warm-Air Furnace Research." Univ. of Ill. Eng. Exp. Sta., Bul. 112, 1919.

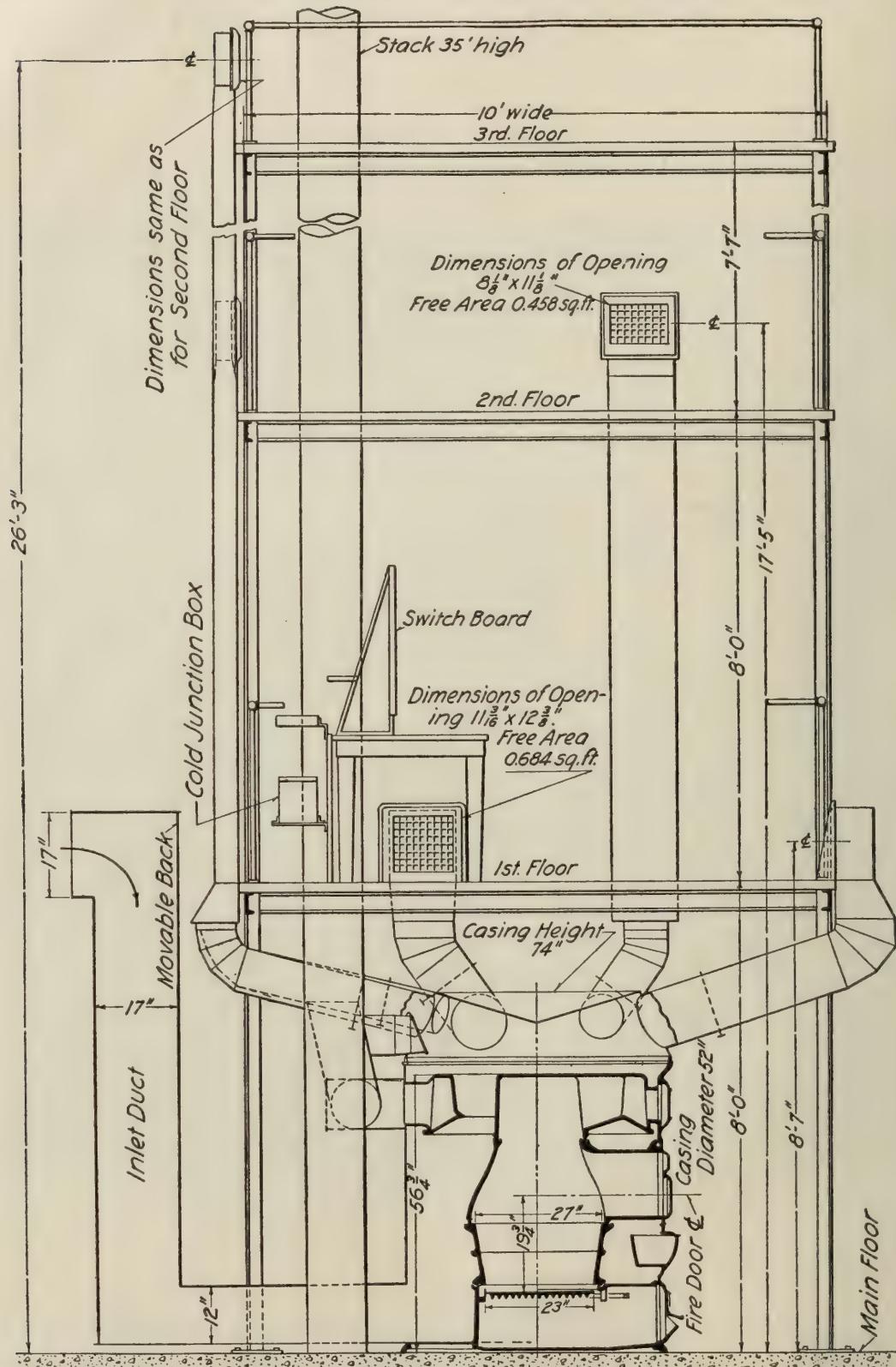


FIG. 3. SECTIONAL ELEVATION OF PIPED FURNACE TESTING PLANT

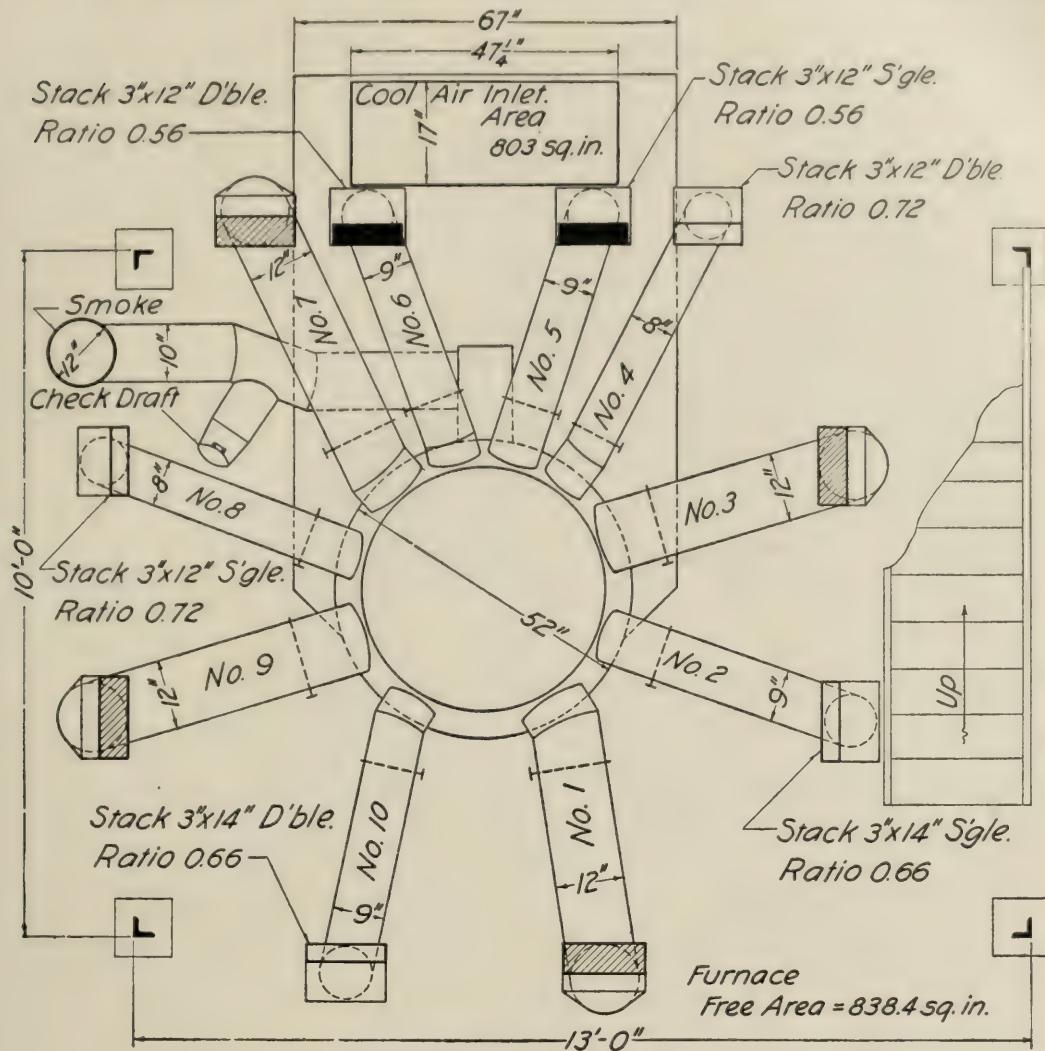


FIG. 4. FLOOR PLAN AND DIMENSION TABLE FOR PIPED FURNACE TESTING PLANT

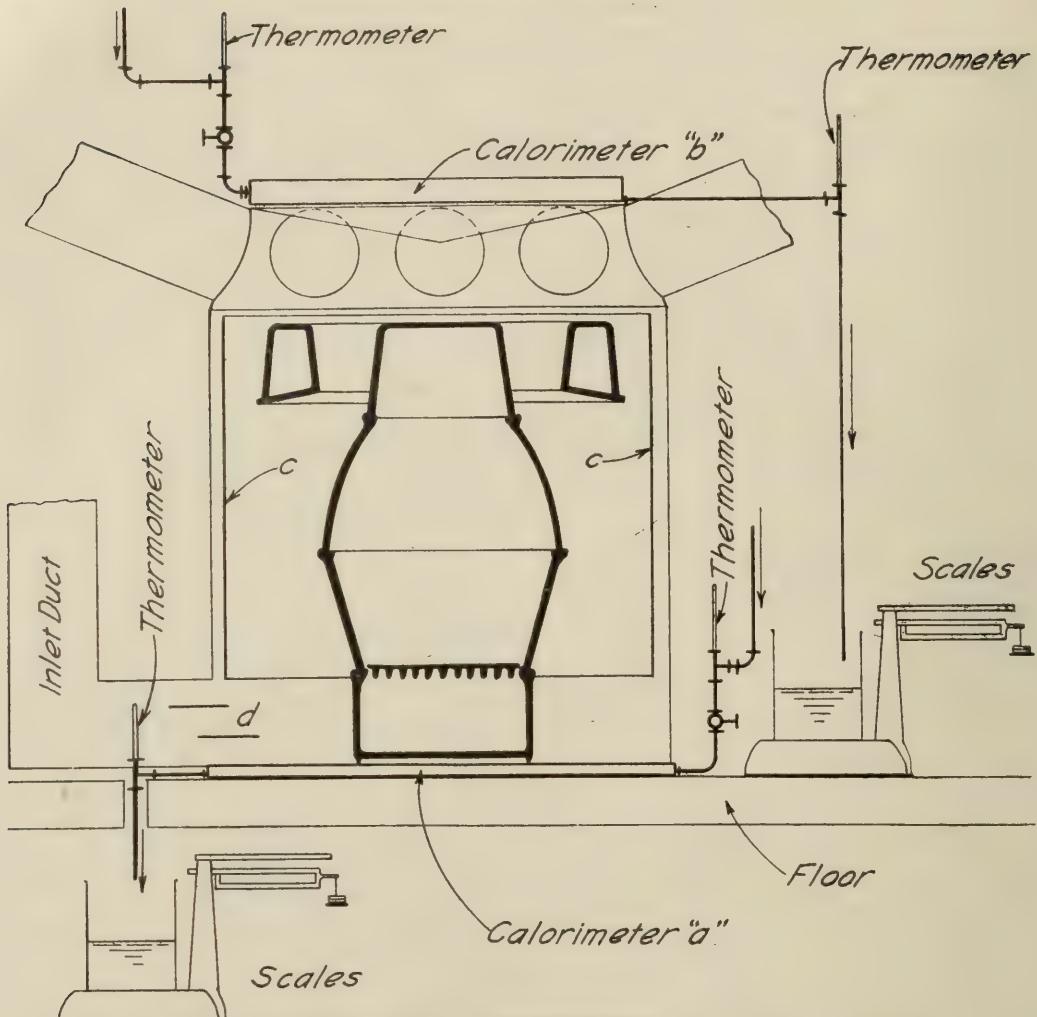


FIG. 5. AUXILIARY TESTING EQUIPMENT FOR PIPED FURNACE

duct enters the furnace casing. These shields also intercept radiant heat and transfer this heat to the entering air in exactly the same way as indicated in (d) for the circular shield.

The balance of the main plant, including all leaders, stacks, and registers, has not been changed, and the original three-story steel structure erected in the Mechanical Engineering Laboratory is still in place. This structure merely serves as the working skeleton of a house and carries the stacks and registers which run to the various floors. All important dimensions are given in the sectional elevation and plan (Figs. 3 and 4), which show the equipment in use on May 1, 1919. These figures are taken from a former bulletin\* and re-

\* "Report of Progress in Warm-Air Furnace Research." Univ. of Ill. Eng. Exp. Sta., Bul. 112, 1919.

beated here for use in studying the performance curves prepared from three tests on this original plant and shown in Fig. 6. A ten-leader plant is still in use and all stacks have been cased in to simulate furred wall conditions. One of the four stacks to the second floor and one of the two stacks running to the third floor are single, but all other stacks are double wall with  $5/16$ -inch air space. The single stacks were made 3-inch deep instead of  $3\frac{1}{2}$ -inch in order to make them comparable with double wall stacks.

8. *Results of Tests.*—The remodelled main plant as described in the preceding paragraphs has not yet been subjected to a complete series of tests. A table of the results of five tests on the original main plant will be found in a former bulletin\* and the results from three of these tests Nos. A-1, A-2, and A-3, have been presented in graphical form (Fig. 6).

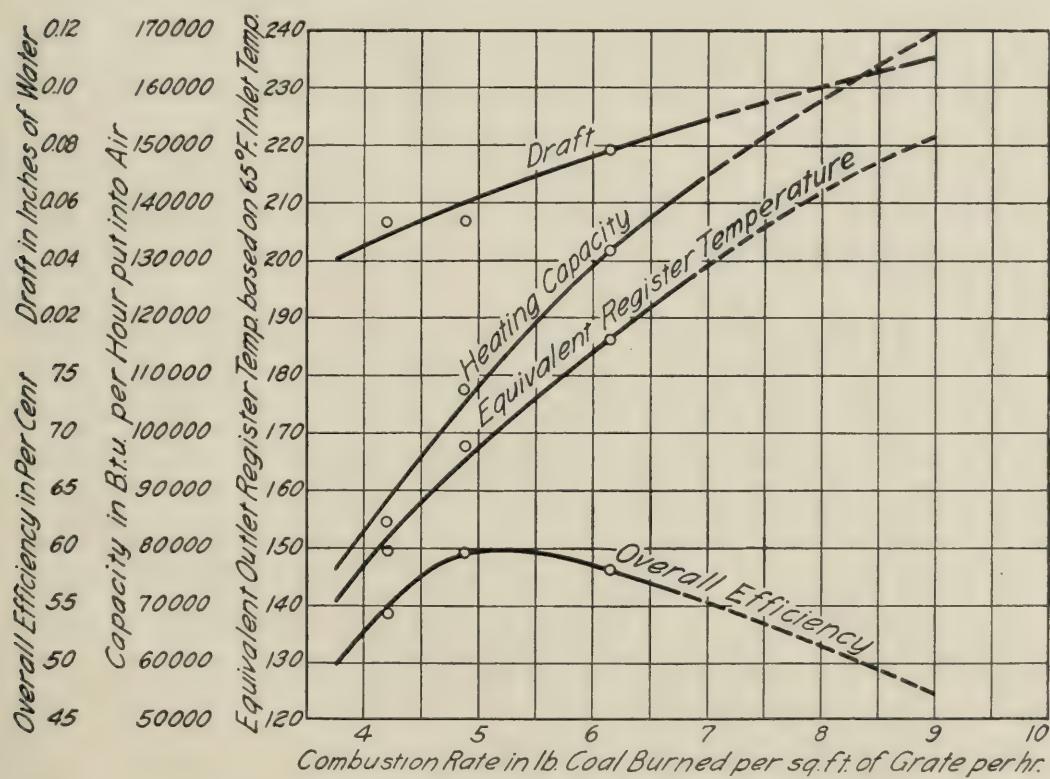


FIG. 6. PERFORMANCE CURVES FOR PIPED FURNACE

\* "Report of Progress in Warm-Air Furnace Research." Univ. of Ill. Eng. Exp. Sta., Bul. 112, Table 5, p. 42, 1919.

9. *Performance Curves from Piped Furnace Plant.*—It has been found practically impossible to make satisfactory comparisons between two or more types of furnaces from a few isolated tests. In fact, comparisons on such a basis may prove very unsatisfactory and lead to erroneous conclusions.

If, on the other hand, the results of a series of tests are plotted on coördinate paper, and the performance curves of the furnace over its entire range of practical operation are drawn, the relation of all factors affecting performance is clearly indicated. Such a series of performance curves is given in Fig. 6 for the piped furnace plant. The rate of combustion is shown along the horizontal axis, and the various curves indicate:

- (a) the draft necessary at the smoke outlet, in inches of water;
- (b) the heating capacity at bonnet in B.t.u. per hour;
- (c) the equivalent register temperature at the register faces based on 65 deg. F. inlet temperature at the recirculating register;
- (d) the efficiency of the furnace in per cent, which is the ratio of the heat put into the air as it leaves the furnace bonnet to the heat value of the coal burned.

As a discussion of a similar set of curves for a pipeless furnace is given in Section IV, reference to that discussion will readily show how to interpret the curves.

10. *Effect of Air Temperature at Register Face and Height of Register above Furnace on Leader Capacity.*—One of the most important results of the work done on the piped furnace plant was the determination of the heat carrying capacity of first, second, and third floor leaders and stacks. These results were given in the first report of progress, but they are so important that it seems advisable to repeat part of the discussion and the plotted results (Fig. 8) in this bulletin.

Curves (Figs. 7 and 8) have been plotted from the data obtained in seven tests on the main plant,\* showing the relation between the register temperatures on any floor, and the B.t.u. carried per square inch of leader pipe per hour to each of these floors.

Knowing the B.t.u. loss per hour from any room on any floor (first, second, or third) and given any register temperature, using the

\* "Report of Progress in Warm-Air Furnace Research." Univ. of Ill. Eng. Exp. Sta., Bul. 112, Table 5, p. 42, 1919.

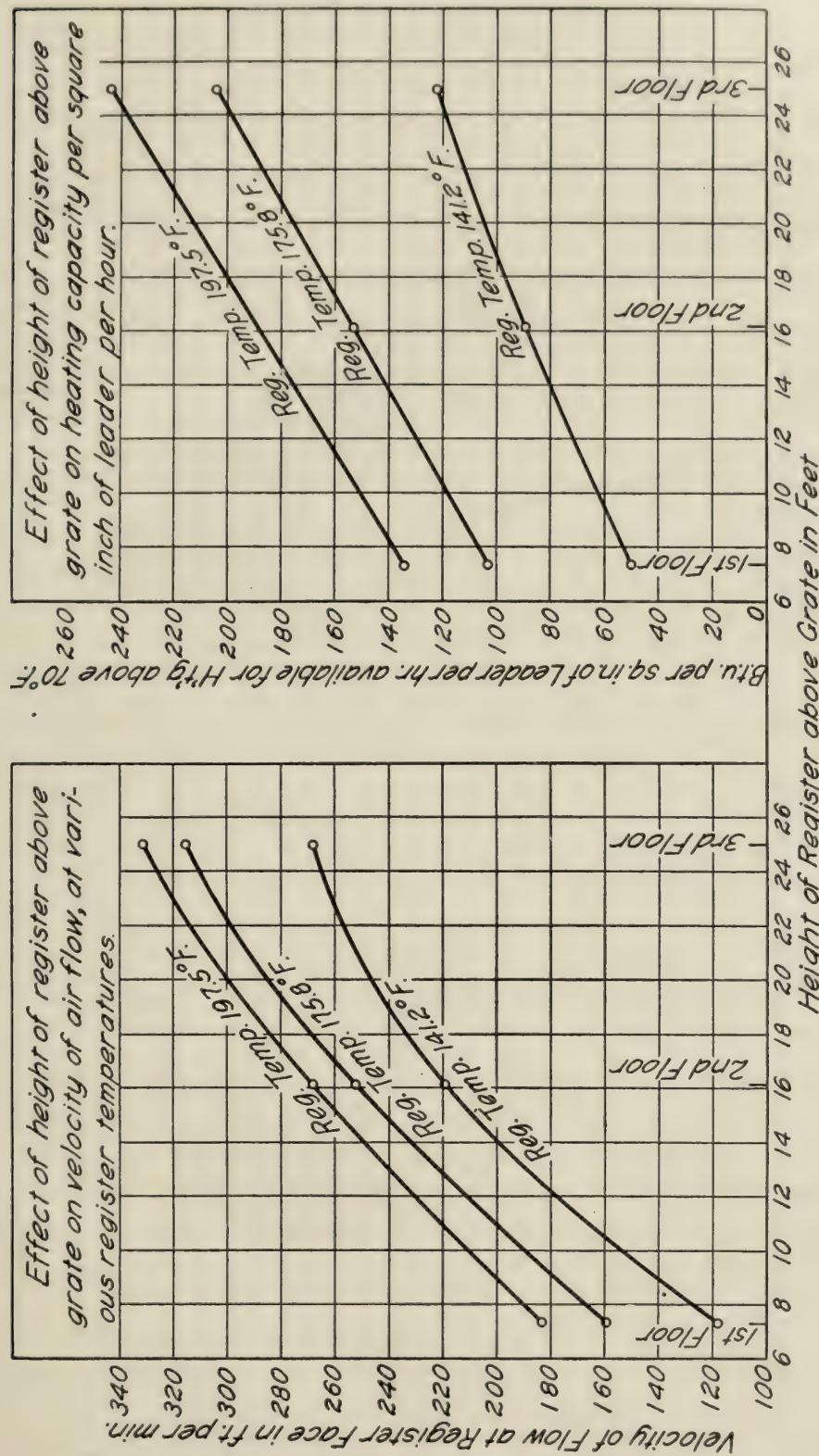


FIG 7. EFFECT OF HEIGHT OF REGISTER ABOVE GRATE UPON VELOCITY OF AIR FLOW AND HEATING CAPACITY

## WARM AIR FURNACE RESEARCH

Subject: Register Temp-  
eratures & Btu. per sq. in. LeaderENGINEERING EXPERIMENT STATION  
UNIVERSITY OF ILLINOIS

Date: 4-29-19.

Name: Pratt, W.E.

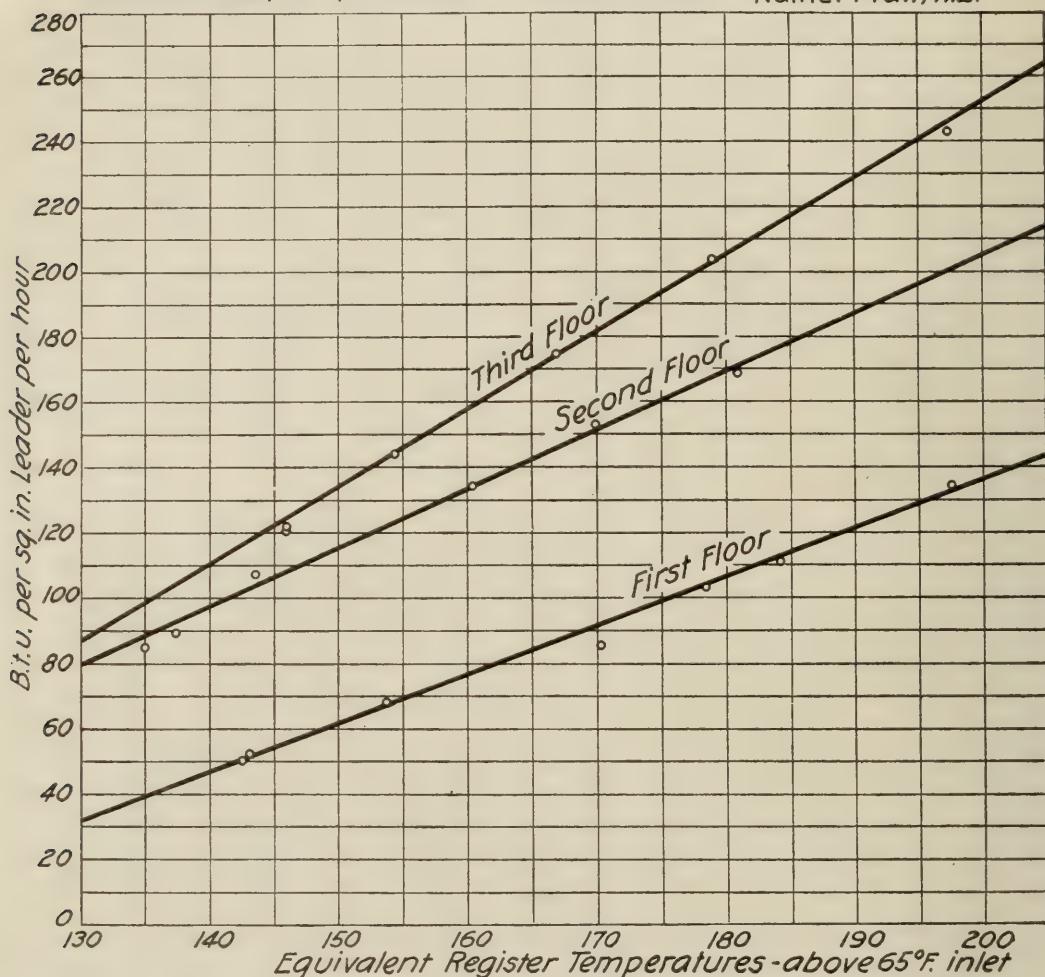


FIG. 8. EFFECT OF AIR TEMPERATURE AT REGISTER ON LEADER CAPACITIES

value of B.t.u. per square inch of leader pipe from these curves (Fig. 8), simple division will give the square inches of leader pipe necessary to heat the room to 70 deg. F. on a zero day.

From the data obtained in the seven tests it was apparent that the temperature at the registers on the second floor was approximately 10 degrees lower than that on the first floor, or about 175 deg. F. In like manner, from the second floor curve, it was found that one square inch of leader pipe at this temperature will supply 160 B.t.u. per hour available for heating rooms. Dividing the heat loss from the second floor rooms by this value gives the square inches of leader pipe necessary to offset the heat loss from the second floor rooms.

In the same way, the test data show a register temperature on the third floor which is about the same as that on the first floor. From the third floor curve it may be seen that at 185 deg. F. register temperature one square inch of leader pipe will carry 215 B.t.u. per hour. The square inches of leader pipe for third floor rooms is found as before.

In plotting the curves the average register temperature for any one floor was used in each case. It was found by reference to the test data that there was a considerable variation in register temperatures on any one floor. It is, therefore, evident that the size of the pipe as figured may not be absolutely correct in each case. It is not much in error, however, and in view of the large increase in pipe areas from one size to the next, the error is negligible for all practical purposes.

It is quite evident that the design of a furnace heating system must be based on the B.t.u. loss per hour from each room. This method of computation is quite familiar to the engineer and can be used by any well qualified furnace man, as fairly simple formulas can be made to cover most types of installation. A later bulletin will cover such applications, and, therefore, no space is given to the calculation of heat losses here.

If, for example, it is found that the living room on the first floor of a house has a heat loss of 16 600 B.t.u. per hour, and a register temperature of 185 deg. F. is to be used, each square inch of leader supplies 115 B.t.u. and the calculated area becomes

$$\frac{16\,600}{115} = 144 \text{ square inches}$$

which requires either one 9-inch and one 10-inch leader, or a special 13½-inch leader.

#### IV. THE PIPELESS FURNACE PLANT

11. *General Description of Plant.*—The plant and the arrangement of equipment for the testing of the pipeless or single register furnace is shown in the general view Fig. 9, and in the sectional elevation Fig. 11. In brief, the plant consisted of a frame structure eight feet in height supporting a platform ten feet square. This platform served as a floor in which was inserted the register, and below this was erected the furnace proper. The main floor of the laboratory was used as the firing floor, and the platform above as the reading or working floor. The chimney was located three feet to the rear of the furnace, and was of 12-inch galvanized-iron pipe 35 feet in height.

The furnace used in these tests was representative of the plain cast-iron horseshoe radiator type, without special radiating surfaces, corrugations, or any special devices for increasing either efficiency or capacity of operation. The fire pot supplied with the furnace was of the slotted type, but fire clay fillers were used to close the slots. For complete data on the furnace shown in the figures see the first page of Table 1.

The following equipment was used in the tests of the furnace: coal and ash weighing and sampling equipment, air measuring devices and calibrating equipment for same, temperature measurement equipment, temperature and draft controlling equipment, draft indicating and recording gages, carbon dioxide indicating and recording apparatus, and a Wahlen gage. The method of furnace testing is given in Section V of this bulletin.

The air measuring equipment is shown in the photographic views of the plant, Figs. 9 and 12, and in the sectional elevations, Figs. 10 and 11. This apparatus consisted of an anemometer with its special register traversing carriage, a cold-air register cover plate with felt gasket and clamping screws, an air supply pipe and damper, shown entering the side of the casing near the floor, a motor-driven blower and speed regulating rheostat, a 10-1/32 inch air measuring pipe with its vertical Pitot tube and piezometer ring and thermometer, and the Wahlen gage. The blower was used to supply a definite amount of

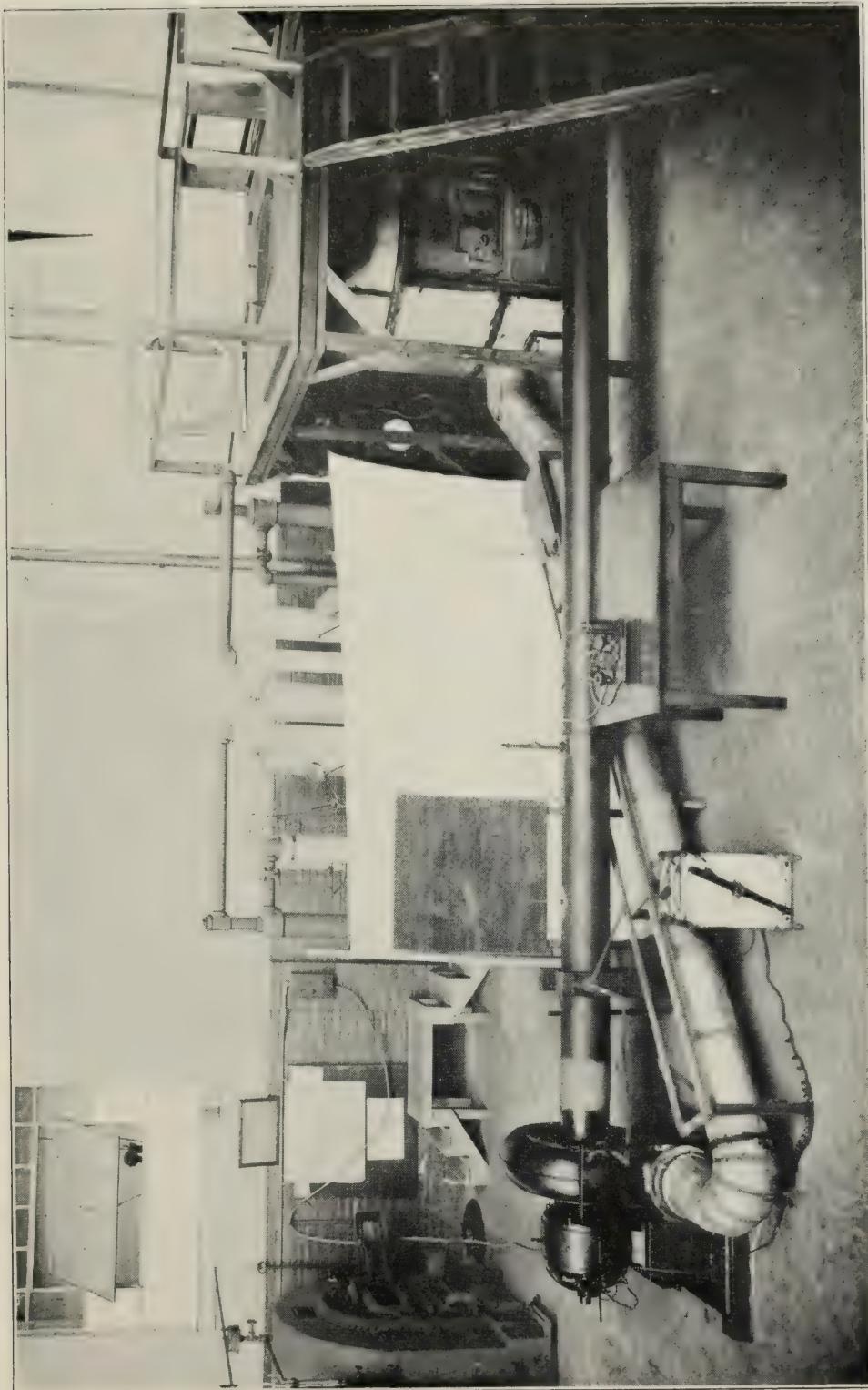


FIG. 9. THE PIPELESS FURNACE PLANT, GENERAL VIEW



Weight of Air per Hour \_\_\_\_\_ lb.  
 B.t.u. per Hour above Inlet T. \_\_\_\_\_ °F.  
 Rise in Temperature of Air \_\_\_\_\_ °F.  
 Register Free Area  $\begin{cases} \text{hot} & \text{sq. ft.} \\ \text{cold} & \text{sq. ft.} \end{cases}$   
 Room Temperature \_\_\_\_\_ °F.  
 Free Area across inner Casing \_\_\_\_\_ sq. ft.  
 Free Area between Casings \_\_\_\_\_ sq. ft.  
 Kind of inner Casing \_\_\_\_\_

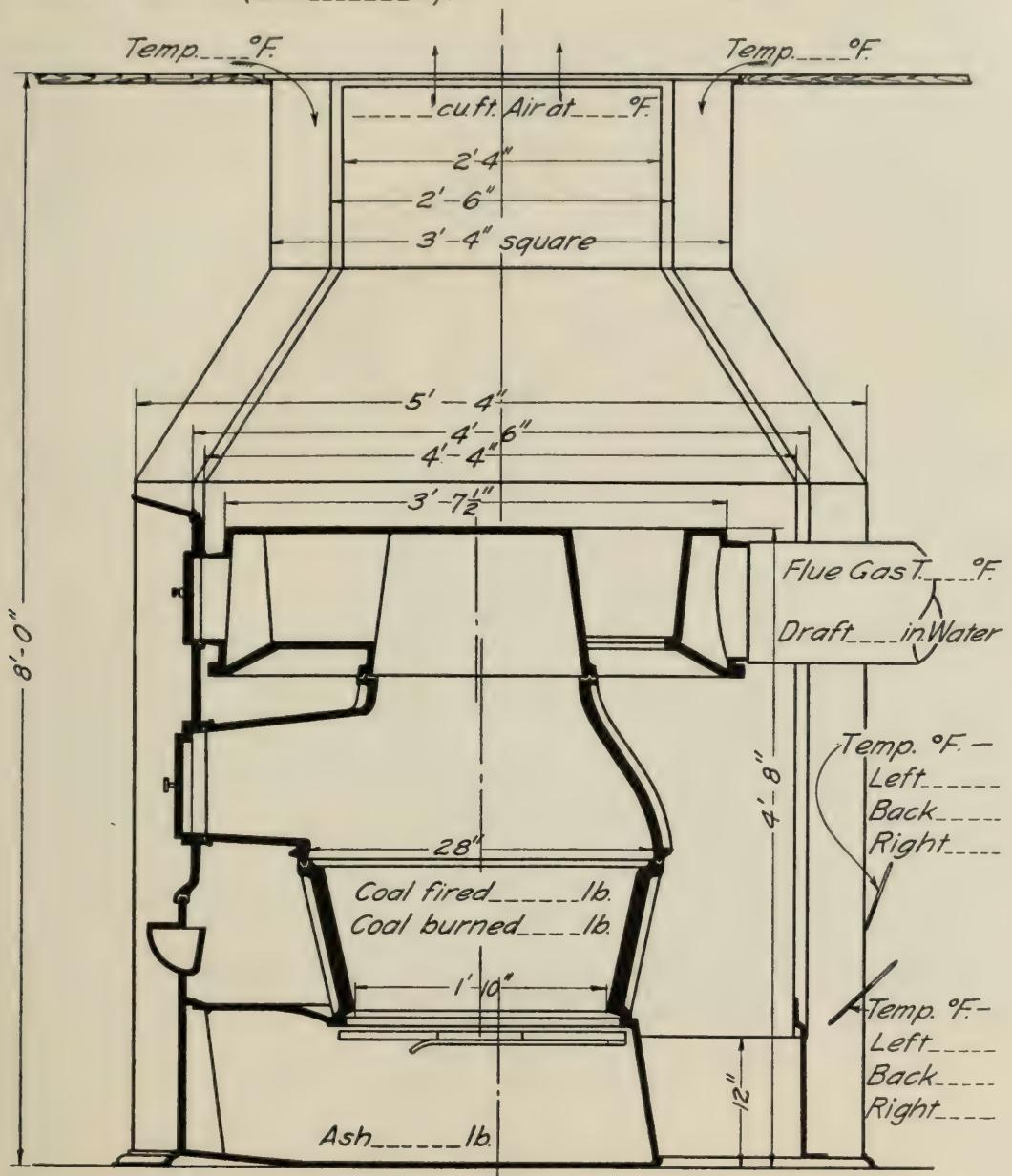


FIG. 10. SECTIONAL ELEVATION AND DATA SHEET OF PIPELESS FURNACE

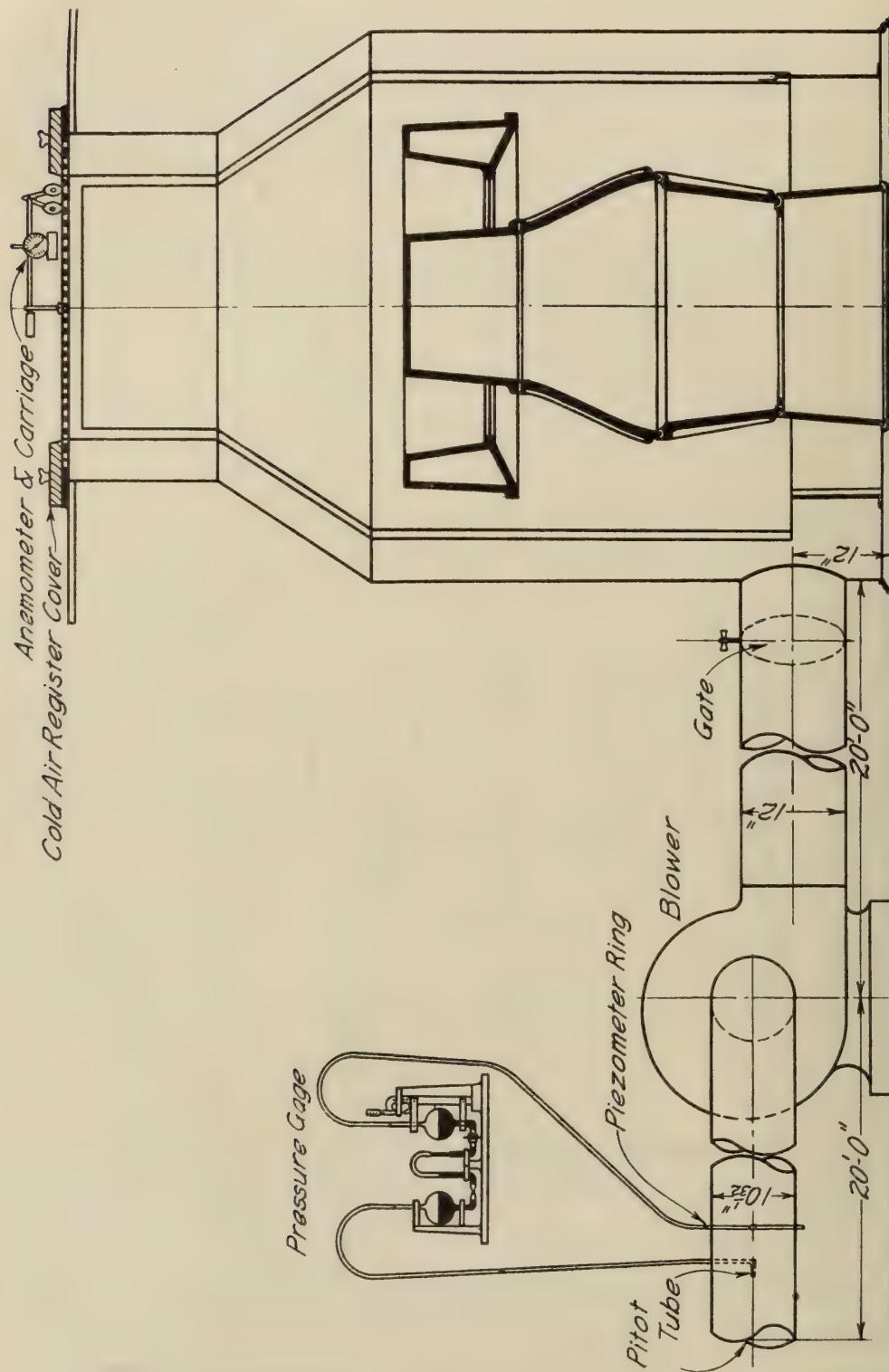
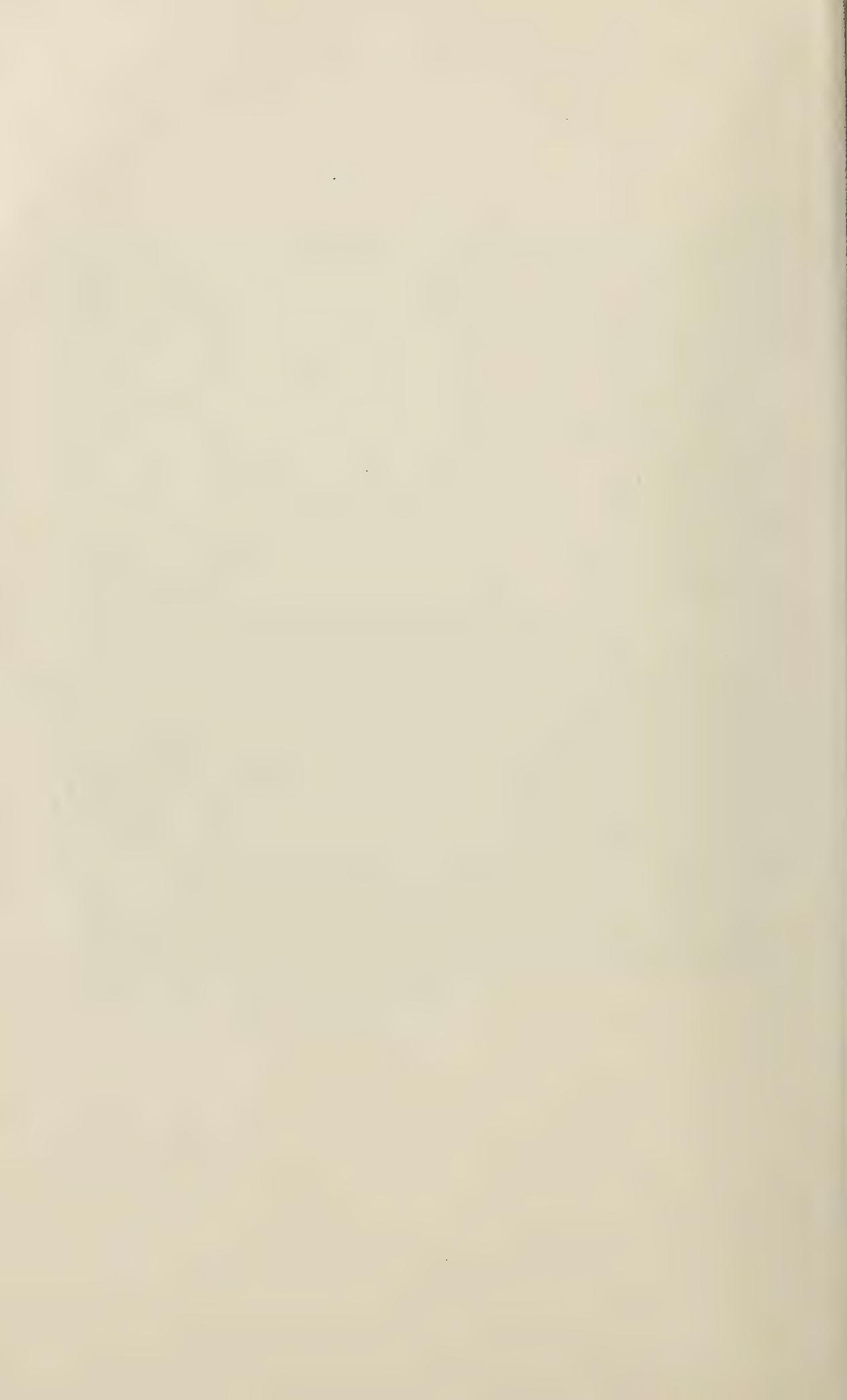


FIG. 11. SECTIONAL ELEVATION OF PIPELESS FURNACE, WITH ANEMOMETER CALIBRATING EQUIPMENT



FIG. 12. PIPELESS FURNACE REGISTER, ANEMOMETER, AND CARRIAGE



air, which was measured by means of the Pitot tube and the Wahlen gage, and this air was then delivered to the furnace and out through the warm-air register. At the register, the anemometer was used to traverse the area and so determine the mean velocity of the air passing the register grille. The speed control of the blower motor made it possible to reproduce any desired velocity of outflow, and a calibration of the anemometer was made for any given register temperature. Such a calibration curve is reproduced in Fig. 13. This method of calibrating the anemometer was particularly advantageous because it was done under exactly the same conditions as existed during a test of the furnace.

The temperature measuring equipment consisted of thermocouples for reading temperatures at points where radiation of heat from the furnace rendered the use of thermometers inaccurate. Thermometers were used at such external positions as were not affected by radiation. A complete discussion of the thermocouple temperature-measurement system is given in Section VI of this bulletin. The central reading station for temperatures indicated by thermocouples may be seen in Fig. 2.

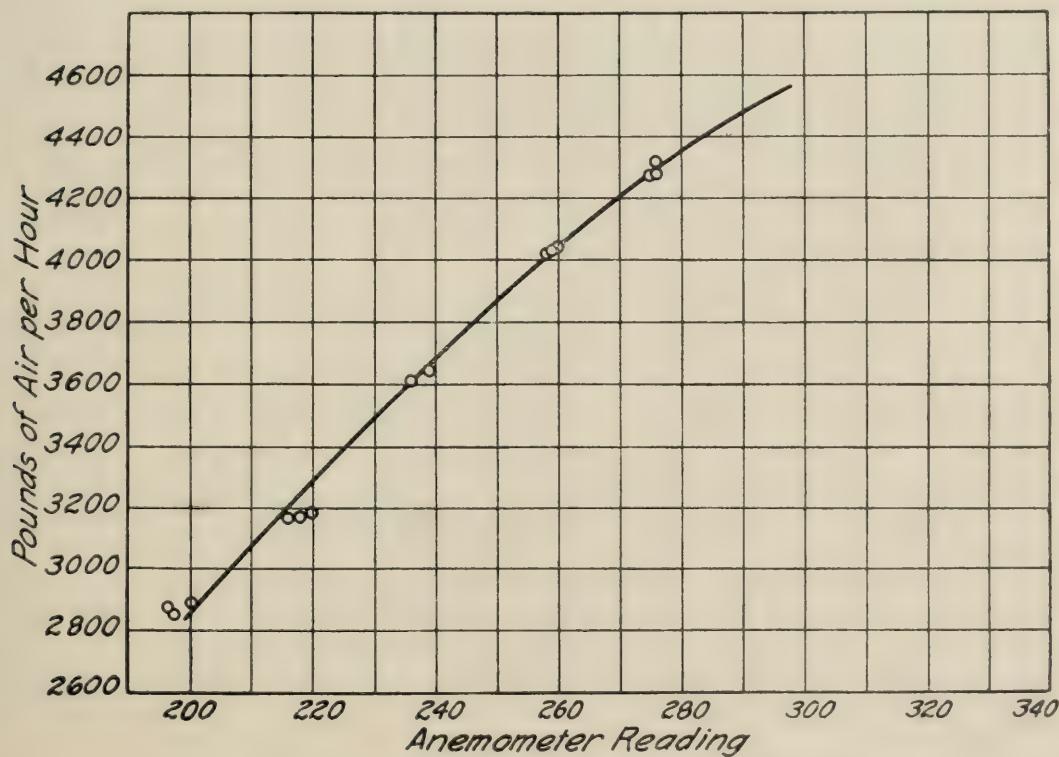


FIG. 13. TYPICAL ANEMOMETER CALIBRATION CURVE

The air temperature controlling mechanism which operated the draft dampers is described in Section V of this bulletin. Successful operation of this device was absolutely necessary in all furnace tests, for upon proper draft control depends the rate of fuel combustion, which affects outlet air temperature, capacity, efficiency, and all other characteristics of operation of the furnace. The device used consisted of a special thermostatic element and mechanism used in conjunction with an electric motor for operation of the air supply damper and the butterfly damper in the smoke pipe of the furnace. Details of the device, described in Section V, are shown in Fig. 16. The importance of maintaining constant conditions in furnace testing cannot be over emphasized, and a uniform combustion rate is absolutely essential. Since draft is the controlling factor in combustion rate it was found desirable to keep a continuous record of the operation of the draft dampers. The draft recorder drew automatically a chart which showed how uniform were the periods of operation of the dampers. Fig. 14 is a reproduction of a chart recorded in an actual test. The draft tube entered the smoke pipe at a point six inches outside the furnace casing. The draft was controlled by a butterfly damper in the smoke pipe, and the ash pit damper. The check damper in the smoke pipe was sealed to prevent any leakage of air into the pipe with consequent errors in the  $\text{CO}_2$  reading. For  $\text{CO}_2$  determinations a recording meter was used.\*

In the conduct of a test on the pipeless plant the services of two men were required, except in calibrating the anemometer, when three were necessary.

*12. Results of Tests.*—The complete data and calculations for the series of twelve tests of the pipeless furnace are shown in tabulated form in Table 1. Test No. 1 was a preliminary test following the erection of the plant. Results of tests Nos. 2 and 3 were given out at the time of the Cleveland Meeting of the National Warm-Air Heating and Ventilating Association, April 21, 1920. Tests Nos. 4, 5, 6, 7, and 8, were made for the purpose of establishing performance curves for the furnace over a wide range of combustion rates. Test No. 9 was made without a warm-air register grille in place. In test No. 10 the fire clay was removed from the slots in the fire pot and hard coal was

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\* "Report of Progress in Warm-Air Furnace Research." Univ. of Ill. Eng. Exp. Sta., Bul. 112.

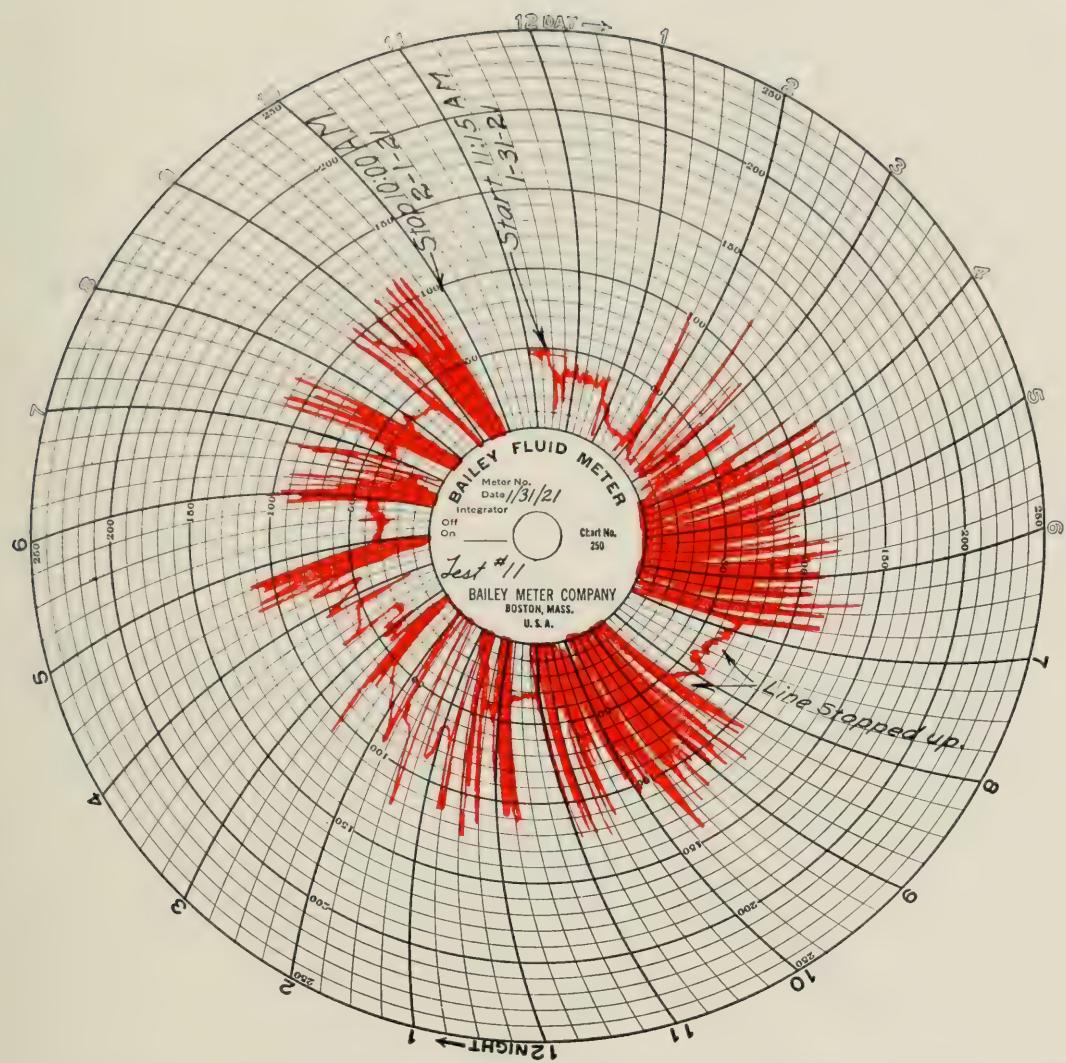


FIG. 14. TYPICAL DRAFT RECORDER CHART FOR PIPELESS FURNACE



TABLE 1

DATA AND RESULT SHEET FOR TWELVE PIPELESS FURNACE TESTS  
At *Mech. Eng'r'g Laboratory, University of Illinois, Urbana, Ill.*

## GENERAL DATA

Built by, <i>omitted</i>	Builder's No., <i>omitted</i> .
Type of Furnace, <i>cast-iron, horseshoe radiator, slotted-pot, slots sealed with fireclay except test No. 10 and 12.</i>	
Type of Inner and Outer Casings, <i>all galvanized iron, inner casing 1-inch air space, feed neck not in cold-air space.</i>	
Type of Grates, <i>duplex, ball-bearing, with shaking ring.</i>	
Type of Chimney, <i>galvanized-iron.</i>	
Type of Register, <i>cast-iron, two piece.</i>	
Rated Capacity, <i>Mfgrs., 40 000 cu. ft. of space.</i>	

## DIMENSIONS

Fire pot diameter at top .....	28 in., at bottom 22 in.
Grate area .....	2.64 sq. ft.
Diameter of outer casing .....	64 in.
Diameter of inner casing, net inside .....	52 in.
Thickness of inner casing .....	1-inch air space
Diameter of radiator .....	45 in.
Distance from outside of radiator to inner casing .....	3½ (mean) in.
Distance between inner and outer casing .....	5 in.
Distance from floor to bottom of inner casing .....	11¼ in.
Least free area across inner casing .....	894 sq. in., 6.21 sq. ft.
Least free area between inner and outer casing .....	693 sq. in., 4.81 sq. ft.
Ratio of cold-air free area to hot-air free area .....	0.774
Throat diameter below register net .....	28 in.
Width and length of cold-air register .....	39¾ in. x 39¾ in.
Net free area of cold-air register .....	488 sq. in., 3.39 sq. ft.
Diameter of hot-air register .....	29¾ in.
Net free area of hot-air register .....	408 sq. in., 2.83 sq. ft.
Ratio free area to gross area of register.....cold air 0.601—hot air 0.630.	
Ratio free area of cold-air to free area of hot-air register .....	1.20
Diameter of smoke pipe .....	10 in.
Height of chimney .....	35 ft.

TABLE No. 1 (CONTINUED)

No.	Name of Item with Units	Date	Test No.	Test No.	Test No.
			1	2 4-15-1920	3 4-17-1920
1.	Duration of test, hr.			12	12
2.	Barometer, inches of mercury			28.90	29.14
3.	Kind of coal	Scranton		Anthracite	
4.	Size of coal	Stove size			
5.	Proximate analysis of coal as fired, per cent:				
6.	Fixed carbon		78.98		
7.	Volatile matter		6.19		
8.	Moisture		1.44		
9.	Ash		13.39		
10.	Sulphur, separately determined		0.81		
11.	Calorific value of coal as fired, by oxygen calorimeter, B.t.u. per lb.			12 791	12 791
12.	Ultimate analysis of coal as fired, per cent:				
13.	Carbon		79.50		
14.	Hydrogen		2.43		
15.	Oxygen		1.68		
16.	Nitrogen		0.75		
17.	Sulphur		0.81		
18.	Moisture		1.44		
19.	Ash		13.39		
20.	Analysis of dry refuse at end of test, per cent:				
21.	Fixed carbon		71.26		73.59
22.	Volatile matter		2.14		2.00
23.	Earthy matter		26.60		24.41
24.	Calorific value B.t.u. per lb.		10 782		11 136
25.	Draft at smoke outlet, in. of water		0.046		0.050
26.	Temperature of outside air, degrees F.				
27.	Temperature of air entering ash pit, degrees F.				
28.	Temperature of inlet air at register face, dry bulb degrees F.		79.8		78.9
29.	Temperature of inlet air at register face, wet bulb degrees F.				
30.	Temperature of outlet air at register face, degrees F.		192.0		184.0
31.	Temperature rise of air from inlet to outlet, degrees F.		112.2		105.1
32.	Equivalent outlet temperature at register face above 65° inlet, degrees F.		177.2		170.1
33.	Temperature of cold air at bottom of inner casing, degrees F.		96.0		94.5
34.	Temperature of outer casing opposite center of fire pot, degrees F.				
35.	Temperature of outer casing 6 ins. above floor, degrees F.				
36.	Temperature of flue gas, degrees F.		543		524
37.	Velocity through free area of outlet register, ft. per min.		368		344
38.	Velocity through minimum free area of furnace, ft. per min.		168		157
39.	Velocity through minimum free area of outer casing, ft. per min.		179		170
40.	Velocity through free area of inlet register, ft. per min.		254		241
41.	Volume of air leaving hot-air register, measured at the actual register temperature, cu. ft. per hr.		62 500		58 500
42.	Volume of air leaving hot-air register, measured at the equivalent register temperature, cu. ft. per hr.		61 000		57 300
43.	Density of air entering cold-air register, lb. per cu. ft.		0.0709		0.0715
44.	Density of air leaving hot-air register, lb. per cu. ft.		0.0587		0.0598
45.	Weight of air circulated per hr., lb.		3670		3500
46.	Weight of air circulated per lb. of coal burned, lb.		304		298
47.	Weight of air circulated per 10,000 B.t.u. supplied in coal, lb.		238		233
48.	Weight of coal fired, total, lb.		250		250
49.	Weight of dry refuse at end of test, total, lb.		124.5		125.2
50.	Weight of equivalent coal in refuse, lb.		105.1		109.2
51.	Net weight of coal burned during test, lb.		144.9		140.8
52.	Combustion rate, pounds of coal burned, per sq. ft. of grate per hr.		4.57		4.43
53.	Heat developed by net coal burned per hr., B.t.u.		154 200		150 000
54.	Heat put into air between inlet and outlet per hr., B.t.u.		98 800		88 300
55.	Heat available above 70° F. for heating house per hr., B.t.u.		94 500		84 000
56.	Heat put into air between inlet register and bottom of inner casing per hr., B.t.u.		14 280		13 120
57.	Total heat put into air which is transmitted by inner casing to entering air, per cent		14.5		14.0
58.	Overall efficiency of furnace, per cent		64.0		58.8
59.	Carbon dioxide in flue gas, per cent		16.0		15.0
60.	Oxygen in flue gas, per cent		3.5		4.5
61.	Heat lost in flue gas per lb. of coal burned, B.t.u.		1867		1893
62.	Heat lost by radiation and "unaccounted for," per lb. of coal burned, B.t.u.		2740		3375
63.	Heat lost in flue gas, per cent		14.6		14.8
64.	Heat lost by radiation and "unaccounted for," per cent		21.4		26.4

TABLE NO. 1 (CONTINUED)

Test No. 4 10-20-1920	Test No. 5 10-22-1920	Test No. 6 10-25-1920	Test No. 7 10-26-1920	Test No. 8 10-27-1920	Test No. †9 12-9-1920	Test No. *10 1-28-1921	Test No. 11 1-31-1921	Test No. *12 2-3-1921
7 29.54 Scranton Anthracite Stove Size	8 29.45 (Tests 1 to 10 inclusive)	9 29.28	10 29.08	12 29.04	10 29.39	9 29.40	36 29.60 Franklin County Bitumin.	36 29.30
.....	.....	.....	.....	.....	.....	.....	50.21 34.83 6.77 8.19 1.04	.....
12 791	12 791	12 791	12 791	12 791	12 791	12 791	12 459	12 459 ]
.....	.....	.....	.....	.....	.....	.....	69.46 4.78 8.38 1.38 1.04 6.77 8.19	.....
62.88	.....	.....	.....	74.24	.....	.....	2.54	10.79
1.76	.....	.....	.....	2.18	.....	.....	.....	.....
35.36	.....	.....	.....	23.58	.....	.....	97.46	89.21
9169	9200	9600	10,530	11,277	10,500	10,600	370	1575
0.158	0.141	0.122	0.085	0.069	0.096	0.17	0.055	0.060
85.0	84.0	70.6	73.1	68.3	76.8	77.5	80.3	84.5
90.3	88.5	80.5	75.8	69.8	79.0	80.4	82.0	86.9
279.0	263.0	247.0	216.0	190.0	217.0	219.0	221.5	227.0
188.7	174.5	166.5	140.2	120.2	138.0	138.6	139.5	140.1
253.7	239.5	231.5	205.2	185.2	203.0	203.6	204.5	205.1
137.0	129.0	110.0	104.0	97.0	107.0	113.4	110.0	116.0
.....	.....	.....	.....	.....	.....	.....	.....	.....
900	825	758	655	520	704	731	733	719
444	434	412	386	341	240	341	355	339
202	198	188	176	155	180	155	162	154
195	193	185	180	164	185	160	161	159
276	274	262	255	232	262	227	235	225
75 400	73 600	69 900	65 500	57 900	67 000	58 000	60 250	57 500
72 850	71 200	68 400	64 500	57 500	65 800	56 700	58 800	55 700
0.0710	0.0710	0.0717	0.0718	0.0726	0.0723	0.0718	0.0722	0.0708
0.0529	0.0538	0.0548	0.0569	0.0592	0.0575	0.0572	0.0574	0.0564
3990	3960	3830	3730	3430	3855	3320	3460	3240
150.0	171.0	195.0	247.0	282.0	252.0	201.0	182.5	203.0
118.0	134.0	152.0	193.0	220.0	197.0	157.0	146.5	163.0
250	250	250	250	250	250	250	684	579
89.7	90.5	98.0	120.5	124.5	118.8	122.2	39.0	33.0
64.1	65.0	73.5	99.2	103.8	97.2	101.0	1.0	4.0
185.9	185.0	176.5	150.8	146.2	152.8	149.0	683.0	575.0
10.05	8.75	7.43	5.71	4.61	5.79	6.26	7.18	6.05
339 600	296 000	251 000	192 800	155 900	195 100	212 000	236 400	199 000
180 800	166 000	153 000	125 500	99 000	127 600	110 500	115 900	109 000
175 800	161 200	148 500	120 800	94 700	123 200	106 500	111 700	105 000
44 800	38 500	27 100	25 230	19 100	24 050	26 300	23 250	22 600
24.8	23.2	17.7	20.1	19.3	18.9	23.8	20.1	20.8
53.4	56.1	61.0	65.1	63.5	65.3	52.1	49.2	54.8
15.0	15.0	14.0	15.0	14.0	14.0	8.5	15.0	13.1
4.5	4.5	5.5	4.5	5.5	5.5	11.0	3.0	4.9
3008	2701	2679	2210	1838	2485	3874	2336	2775
2952	2910	2307	2251	2832	1956	2257	3993	2854
23.4	21.1	21.0	17.3	14.4	19.4	30.3	18.8	22.3
23.2	22.8	18.0	17.6	22.1	15.3	17.6	32.0	22.9

\* Slots in fire-pot open.

† No register grille at outlet.

used. Tests Nos. 11 and 12 were made with soft coal with slots closed and open, respectively.

The data compiled in Table 1 were arranged in accordance with the Pipeless Furnace Testing Code, which is discussed in Section V of this bulletin. This section deals with the methods used in all these tests.

It will be noted that in all the hard coal tests, Nos. 1 to 10 inclusive, the fuel was taken from the same supply. The analysis given in the table was made from a representative sample taken from thirty tons of Scranton stove size anthracite coal. Analyses of the ash and refuse were not made for all tests. Instead the data on "Heat Value of Residual" (See Section V) were used for determination of the heating value of the ash and refuse.

13. *Performance Curves from Pipeless Furnace Plant.*—The tests Nos. 4 to 8 inclusive were made for the purpose of obtaining complete performance data for the furnace and were the most important of the series. The principal performance data obtained from the tests have been plotted in curve form, Fig. 15. These curves

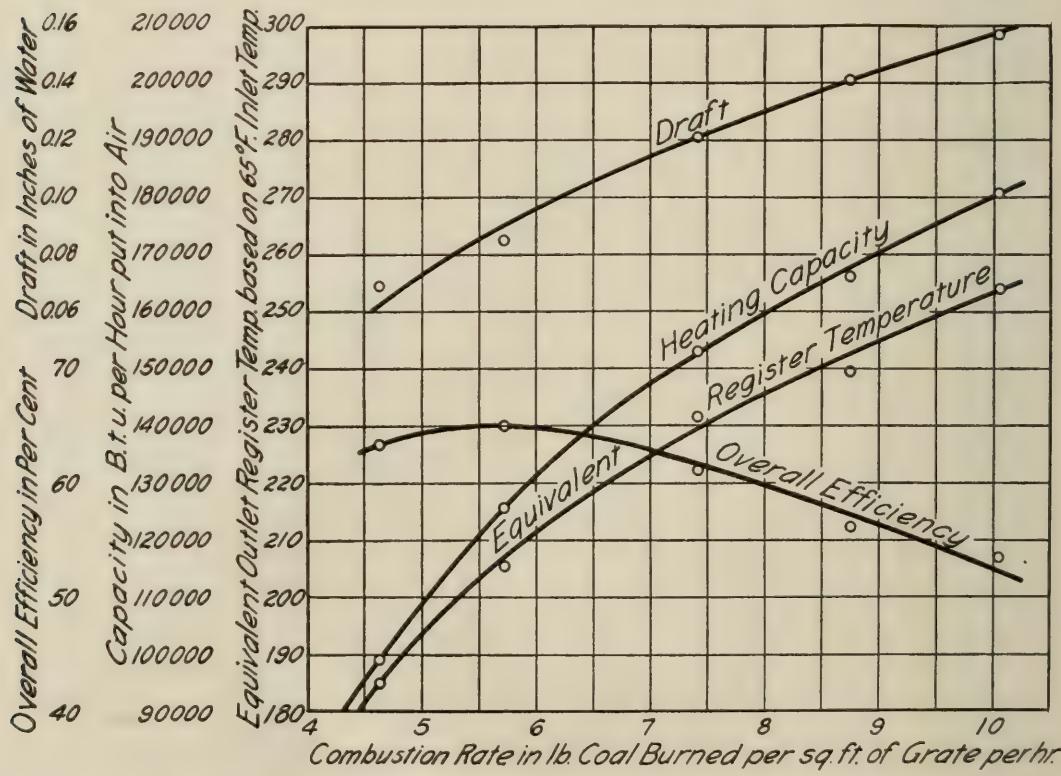


FIG. 15. PERFORMANCE CURVES FOR PIPELESS FURNACE

emphasize the following factors, all of which are essential to the proper design, installation, and operation of a furnace:

- (a) the rate of combustion (pounds of coal burned per square foot of grate per hour);
- (b) the efficiency of the furnace (ratio of heat put into air passing furnace to total heat value of coal burned, usually expressed as a percentage);
- (c) the capacity of furnace in B.t.u. (British thermal units) per hour, which is the heat put into air passing through furnace per hour;
- (d) the equivalent register temperature of air leaving register based upon 65 degrees Fahrenheit inlet temperature; to get the actual rise in temperature it is only necessary to subtract 65 from these register temperature values;
- (e) the draft at the smoke outlet of the furnace in inches of water, which indicates the great importance of providing a satisfactory chimney if the full capacity of the furnace is to be realized. This curve also shows that capacity is entirely dependent on draft for a given furnace and a given coal.

Since draft is the controlling factor in testing it is desirable to consider an example of its effect. Refer to Fig. 15, and select a combustion rate of 5.5 pounds of coal per sq. ft. of grate per hour, and obtain the following values from the curves:

1. Combustion rate = 5.5 pounds per sq. ft. grate per hour.
2. Draft = 0.085 inches water.
3. Efficiency = 65 per cent.
4. Heating capacity = 121 000 B.t.u. per hour.

Now assume that a better chimney is provided and that the draft is thereby increased. Note then the following results corresponding, for this furnace, to a draft of 0.155 inch of water:

1. Combustion rate = 9.8 pounds per sq. ft. grate per hour, an increase of 78 per cent.
2. Draft = 0.155 inches water, by hypothesis.
3. Efficiency = 53 per cent, a marked decrease; but
4. Capacity = 178 000 B.t.u. per hour, an increase of 47 per cent; and
5. Equivalent register temperature = 252 deg. F., an increase of 25 per cent.

It will also be evident that high capacity from this furnace was attained at a loss in efficiency. In the above example, an increase in capacity of 47 per cent was indicated, but the increase was obtained by an increase in the coal burning rate of 78 per cent. It should be borne in mind that the efficiency of a pipeless furnace may safely be estimated as higher than is indicated by the curve, because of the large amount of heat energy radiated through the register that is not measurable, but is useful in heating. This has been estimated at 9 per cent, as stated in the discussion of heat losses from a pipeless furnace, Section X.

The significant conclusions arrived at by this method of showing rating and performance data are of the greatest value in aiding in the selection of the proper furnace, or in comparing two furnaces, or a furnace and boiler. As an example, assume that the heat loss from a certain house is 170 000 B.t.u. per hour in the very coldest weather, which lasts for only a few hours, and that the heat loss under average cold weather conditions, which last for many hours, is only about two-thirds of this, or 113 000 B.t.u. per hour. It will be at once apparent that this furnace will handle the average cold weather load at very nearly its highest efficiency, which the efficiency curve shows to be 65 per cent, at about this rating.

This same furnace, as shown by the rating and performance curves, has a heating capacity of 178 000 B.t.u. when burning coal at a combustion rate of 9.8 pounds per square foot of grate with a draft of 0.155 inches water. It would also, therefore, readily handle the severest heating load during the winter, *provided the chimney in the house could develop a draft of 0.155 inches of water.*

The furnace would, of course, be operating in the latter case at an efficiency of only 53 per cent, with an outlet register temperature of 252 deg. F., as shown by the curves at 9.8 pounds combustion rate. This reduced efficiency and high register temperature are not serious matters, however, as the very severe conditions last only a few hours.

It should be noted that in the example just discussed not only has the register temperature increased from 203 deg. to 252 deg. F., but the weight and volume of air passing the furnace has also increased.

In Table 1 may be found much data which will be useful in the design, selection, and operation of a furnace, such as flue gas temperature and heat loss, extent of premature heating of air in the outer casing, total heat loss from the furnace, air handling capacity

in cubic feet and in pounds, velocity of air movement at various points in the system, and percentage of fuel consumed for a wide range of furnace operation.

Test No. 10, made with a slotted pot, makes it plain that the slotted fire pot should not be used with hard coal as fuel. By comparing the tabulated data of this test with that of test No. 7, in which the same air temperature-rise was maintained, it may be seen that the heating capacity fell from 125 000 to 110 000 B.t.u. per hour, that the open-slotted pot efficiency was only 52 per cent, as against 61 per cent for the closed-slotted pot, that much more coal was consumed (in the ratio of 6.26 to 5.71), and that in order to maintain this extra rate of combustion a draft of 0.17 inches of water, as against 0.085 inches in the closed-slotted pot, was necessary. This indicates that in installations in which good chimneys are not provided it would be difficult to burn hard coal in an open-slotted-pot furnace.

Tests Nos. 11 and 12 were run with a good grade of Illinois bituminous coal with closed-slotted and with open-slotted pot, respectively. Some advantage is shown for the open-slotted pot in these tests. A discussion of the effect of the slots upon furnace performance is included in Section XII of this bulletin. These two tests were of 36 hours duration each, and the experience with them indicates that on account of difficulties of gaging the fire condition at the beginning and end of tests, a test period of more than 36 hours is advisable. For purposes of comparison between the soft coal and hard coal tests reference should be made to tests Nos. 11 and 7 respectively.

Test No. 9 was made as a check upon test No. 7, except that the register grille was removed in test No. 9 for the purpose of observing the effect of the grille in decreasing the air handling capacity. A discussion of this effect is given under Section XIII in the paragraphs on losses in register grilles.

In Section III on the Piped Furnace Plant are shown a set of performance curves (Fig. 6), which will serve for comparison with the performance curves of the pipeless furnace. For further comparison of piped and pipeless furnaces the data given in Table 1 should be compared with the data given for piped furnaces in a former bulletin.\* It must be borne in mind that the two furnaces, although

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\* "Report of Progress in Warm-Air Furnace Research." Univ. of Ill. Eng. Exp. Sta., Bul. 112, Table 5, p. 42, 1919.

similar, were not identical in castings sizes, and any close comparisons are hardly justified.

**14. Proportions of Casings for Pipeless Furnaces.**—The question of the proper proportions of the casings for pipeless furnaces has been given some consideration but as yet very little actual data have been obtained. From the purely theoretical standpoint, the air should be taken at the bottom of the inner casing from a large reservoir of cold air where the velocity is zero. This is impracticable, however, because air must not be taken from the basement floor, for sanitary reasons. Moreover, the radiation from the fire pot heats the inner casing of a pipeless furnace, and the air must therefore move over the casing surface at some velocity in order to absorb this heat and deliver it into the space to be heated. Any heat absorbed by the down-coming air, of course, decreases the capacity somewhat, because the air should be cold at the bottom of the casing in order to obtain the maximum difference in density of the air column inside and outside the furnace, or in other words to obtain the maximum driving head. Since some velocity downward over the surface of the inner casing is necessary, the question arises as to exactly what velocity should be maintained.

In order to reduce the head loss through the furnace to a minimum, there should be as few changes in velocity as possible, since every velocity change entails loss of head. This condition is realized when the ratio between the minimum free area across the inner casing and the area between the two casings is made equal to the inverse ratio of the densities of the air in the two spaces. The air leaves the register in the average pipeless furnace at approximately 220 deg. F., and enters the cold air face at approximately 70 deg. F. The corresponding densities are 0.0584 and 0.0749. Hence the area between casings should be made about  $\frac{0.0584}{0.0749} = 0.78$  of the free area through

the inner casing. These proportions have proved satisfactory in practice. If the area between casings is made materially larger than 0.9 of the free area through the inner casing, the downward movement of air in the cold-air space becomes less positive, and finally a point is reached where eddy currents are set up. These eddies carry heat directly from the inner casing to the outer casing, thus increasing the heat loss, and decreasing the efficiency. At the same time the air

TABLE 2  
EFFECT OF CASING PROPORTIONS ON PIPELESS FURNACE EFFICIENCY AND CAPACITY

Test No.	Warm-Air Free Area through Furnace Sq. Ft.	Ratio of Cold-Air Free Area to Warm-Air Free Area through Furnace	Capacity in B.t.u. Put into Air per Hour. Temperature Rise 184° F.	Efficiency of Furnace Per Cent	Combustion Rate Lb. Coal per Sq. Ft. Grate per Hour	Flue Gas Temperature Degrees F.	Per Cent Heat Put into Air Which Is Transmitted by Inner Casing to Entering Air	Temperature of Outer Casing Opposite Center of Fire-pot, Degrees F.	Inner Casing Construction
									Single Single Single Double Air Space
1	1.96	0.89	65 400	53.5	5.60	564	26.0	111.0	
2	1.96	2.72	88 750	48.1	8.32	643	52.0	132.0	
3	2.89	0.77	96 300	54.0	8.05	579	29.0	99.0	
4	2.97	0.90	99 000	51.3	8.80	691	19.0	90.0	

becomes more heated between the casings, decreasing the difference between the densities of the air inside the inner casing and of that between the casings, respectively, thereby reducing the available head. The eddy currents also serve to use up more of the available head under which the furnace is operating. How far the ratio under discussion may be increased before eddy currents appear has not been determined.

Table 2 gives the results of four tests made with the same set of castings encased in three different ways.

In the first test, a furnace was used in which the inner casing was of black iron lined with asbestos and corrugated tin. The proportion between the cold-air and warm-air areas was about correct, but the casings were too small for the castings used. Increasing the cold-air space for test No. 2 increased the capacity. The cold-air space was increased entirely too much. This resulted in the eddy currents already referred to transferring heat to the outer casing, as shown by the fact that the casing temperature increased from 111 deg. F. to 132 deg. F. The efficiency was reduced from 53.5 to 48.1 per cent by this loss of heat. The increased flue gas temperature due to the increased combustion rate also tended to decrease the efficiency. Apparently the decrease in resistance through the furnace resulting from opening up the cold-air space was more than sufficient to offset not only the handicap of the eddy currents in the cold-air space, but also the fact that the air was delivered to the bottom of the casing at a much higher temperature in the second case, since the capacity increased from 65 400 to 88 750 B.t.u. per hour.

For test No. 3, the asbestos and tin lined inner casing was retained, but the free area on the warm-air side was made larger, and the cold-air space given the proper proportion of area. This raised the capacity to 96 300 B.t.u. per hour. The temperature of the outer casing was reduced to 99 deg. F. and the efficiency increased to 54 per cent. For test No. 4, the warm-air area was still further increased and a double inner casing with a 1-inch air space was used. The capacity was raised to 99 000 B.t.u. per hour. The casing loss was materially decreased, the casing temperature being reduced to 90 deg. F. At the same time, much less heat was put into the air before it reached the bottom of the casing than in the other cases. The high flue gas temperature resulting from the high combustion rate necessarily reduced the efficiency to 51.3 per cent, but the furnace used in

test No. 4 still compares favorably with the other furnaces, and is much better than the one used in test No. 2. Taking all factors into consideration, the fourth furnace is the best one tested.

Some work has been done to determine the proper height from the floor for the bottom of the inner casing. By using smoke bombs at the cold air face and observing through a glass window at the bottom of the outer casing the path taken by the smoke, it was found that all the air makes the turn at the bottom within a space of 8 inches. If the height of the bottom of the inner casing was greater than this a clear space was observed along the floor. Therefore, from 7 to 9 inches is considered the correct height. This causes the air to sweep along the floor when the turn is made and allows it to absorb some of the heat which the floor has received as radiation from the fire-pot.

In proportioning the registers for a pipeless furnace, a logical rule seems to be that the mean between the warm-air throat area and the free area of the warm-air register face should be equal to the minimum free area of the warm-air space across the inner casing. These were the proportions used in the best furnaces discussed in the preceding paragraphs. No attempt has been made to isolate this as a single factor, however, but such a practice will result in the minimum velocity change in the air flow at these three levels.

## V. METHOD OF TESTING WARM-AIR FURNACES

15. *Quantities to be Measured.*—The complete test of a warm-air furnace involves the measurement of three principal quantities. These are:

- (a) the weight of coal or other fuel actually burned during the test;
- (b) the rise in temperature of the air passing through the furnace casing;
- (c) the weight of air passing through the casing during the test.

Since either hard or soft coal may be used in operating furnaces, the testing procedure must provide for both fuels.

16. *Tests with Hard Coal as Fuel.*—For the tests with anthracite, a single charge of coal was used, and the firing period was determined by the time required to burn out this charge. The fire was not disturbed after the last shovelful of coal was fired. In no case was a test continued for a longer time than that required to leave a 20 per cent reserve of fuel for the next firing, and in some cases of low combustion rates the length of test was arbitrarily made 12 hours. The normal firing period was about 8 hours.

A depth of fuel bed of 17 inches brought the top of the bed level with the feed neck. This amount of coal was determined upon as the normal charge, and amounted to 250 lb., which was used in all cases.

In starting a test, a charge of dry wood equal in weight to 10 per cent of the fuel charge was first fired. This charge was allowed to burn for about 10 minutes, and then the coal was fired. The test started when the first coal was fired, and with the ash pit clean. In some of the earlier tests, the coal charge was divided into three parts. The first third was fired when the wood had burned 15 minutes, the second third 15 minutes later, and the last third at the end of another 15 minutes. Thus all the coal was fired in one half-hour. In the later tests, firing started when the wood had burned 10 minutes, and continued in small amounts for about an hour, all the charge having been fired by the end of this time. In all tests readings were taken every 5 minutes for the first hour or hour-and-a-

half, and these readings were plotted against time, the curve thus obtained giving a record of progress until the predetermined temperature-rise for the test was reached. An attempt was always made to reach running conditions in about an hour. After the running temperature was attained, readings were taken every 30 minutes. In averaging results, the 5-minute readings were divided into half-hour periods and averaged for each half-hour period; these averages were then averaged with the rest of the 30-minute readings.

At the close of a test, the fire was quenched by using a small stream of water from a hose, care being taken to direct the full force of the stream into the bed in order to avoid cracking the castings. No damage has ever resulted from this practice. In the earlier tests, the residue left after the fire had been quenched was dried and weighed and a sample taken for analysis. From this analysis the heating value was obtained, and the residue was reduced to terms of equivalent coal by multiplying the weight of residue by the ratio of the heating value of the residue to the heating value of the coal. This result was then subtracted from the weight of coal fired and the difference designated as the net weight of coal burned during the test. (See item 51 in the pipeless furnace code following.) The analyses showed, however, that practically all of the combustible in the residue was fixed carbon. This made it unnecessary to have an analysis made each time, as the heating value could be directly calculated. The residual was taken from the ash pit as usual, and very thoroughly dried. Since the draft was always low, less than 0.2 inch of water, all the ash resulting from the original coal charge should be in the residual at the end of the test. If  $W_1$  represents the weight of the coal charge,  $A_1$  the percentage of ash in the coal, and  $W$  the

weight of the ash in the residual, then  $W = \frac{A_1 W_1}{100}$  The weight of

carbon  $C$  in the dry residual is then  $= W_2 - \frac{A_1 W_1}{100}$  in which  $W_2$

= the weight of the dry residual. Every pound of carbon has a heating value of 14 600 B.t.u. Let  $H_1$  = the heating value per pound of the coal,  $H_2$  = the heating value per pound of the residual, and  $W_3$  = the equivalent coal value of the residual; then

$$H_2 = \frac{14,600}{W_2} \left( W_2 - \frac{A_1 W_1}{100} \right)$$

$$W_3 = \frac{H_2 W_2}{H_1} = \frac{14,600}{H_1} \left( W_2 - \frac{A_1 W_1}{100} \right)$$

The net weight of coal burned in test =  $W_1 - W_3$ .

It is believed that the error in using this method is less than the combined error of sampling and analyzing, since it is rather difficult to obtain a truly representative sample. Table 3 shows a comparison of the weight of equivalent coal calculated from the analysis of the residual and by the preceding method.

It may be noted that the greatest difference is approximately one per cent, if test No. 3 is excluded. It is probable that the error in test No. 3 occurred in sampling the residual.

TABLE 3  
COMPARISON OF RESULTS OBTAINED BY DIFFERENT METHODS OF  
DETERMINING WEIGHT OF COAL BURNED

Test No.	Heating Value of Residual by Analysis B.t.u. per lb.	Coal Burned Calculated from Chemical Analysis, Lb.	Coal Burned Calculated from Formula, Lb.
2	10,328	105.1	103.8
3	10,989	109.1	104.5
4	8,563	64.3	64.1
8	11,215	104.2	103.8

17. *Tests with Soft Coal as Fuel.*—In the case of anthracite coal, the fuel bed required no attention after all the coal was fired. For bituminous coal, however, the case was different. A thinner bed was required, and unless it was given attention the coal burned unevenly and formed holes in the fire, with a consequent reduction in efficiency. If an attempt was made to start with clean grates and to fire a large charge, it was found to be impossible to control the temperature at the register face for the first  $2\frac{1}{2}$  hours or more. A temperature much too high would be attained at the start and thus unbalance test conditions for the remainder of the test. A different method, therefore, had to be adopted.

It was estimated that an error of approximately 20 pounds of equivalent coal could be made in judging the condition of the fuel bed. Calculation showed that it was necessary to burn 650 pounds of coal

on a test in order to reduce this error to 3 per cent, and to burn 650 pounds of coal required 36 hours. The soft coal tests were accordingly run for this length of time.

Before starting a test, the furnace was operated at the rate required on the test for a period of about 12 hours in order to accumulate enough ash in the fuel bed to correspond to normal operating conditions. The grates were then shaken until live coals just appeared, and the ash pit was cleaned. The test started at this time. Coal was fired in small charges once an hour and the fuel bed was leveled after each firing. This was continued for 36 hours, and the test was stopped with the fuel bed in the same condition as it was at the start, so far as it was possible to estimate it from its appearance. Just before stopping, the grates were again shaken until live coals appeared, the ash pit was again cleaned, and the total ash taken out during the test was weighed.

This method of firing does not exactly correspond to that used in house service, but if the fuel bed is not given attention for periods of 3 hours or more, wide discrepancies appear due to differences in fuel bed conditions, and the tests become worthless for purposes of comparison.

*18. Importance of Temperature and Draft Control in Furnace Testing.*—The most important single factor which could be used as a reference quantity in all these tests was found to be the rise in temperature of the air passing through the furnace casing. The temperature-rise in turn is dependent upon the rate of combustion or the draft, but it is much more convenient to use the temperature-rise for this purpose than any other observed quantity. Moreover, it was soon found that the value of a test was determined almost entirely by the relative constancy of the temperature-rise of the air; large fluctuations in the rise in air temperature during a test made the comparison of such a test with other tests of little significance. If the rise in temperature was maintained constant, then all other factors in the test also remained constant, and a great deal of attention was, therefore, given to apparatus which would indicate the temperature-rise, and at the same time control this rise. The accurate determination of the actual temperature of the air leaving the register was also of great importance.

A study of the graphical log sheets made during each test, in which the anemometer readings and register temperatures were plotted against time, showed a practically constant relation between the anemometer reading and the register temperature for any given test. This led to a method whereby the number of anemometer readings could be reduced to a minimum. Table 4 shows the relation between anemometer readings and temperature-rise for one test, the readings having been taken simultaneously.

It may be noted that in very few cases in this particular test do the individual ratios of anemometer readings to temperature-rise deviate materially from the average 1.043.

A simplified method of testing is therefore possible. After test conditions have been reached and the predetermined temperature-rise for a particular test has become constant, several simultaneous readings of the anemometer and the temperature are taken. After this, anemometer readings are discontinued and *especial care exercised to maintain the temperature-rise constant*. At the end of the test, the anemometer reading is obtained by multiplying the average temperature-rise by the ratio of anemometer reading to temperature-rise found from the readings taken at the beginning of the test. This method also has the advantage of saving the anemometer, which is a delicate instrument, from wear and abuse.

Since, in running comparative furnace tests, too much emphasis cannot be placed upon the maintenance of a constant temperature-rise, an attempt was made to control the furnace drafts automatically in order to accomplish this end. It was soon found that the expansion members of most commercial regulators had too much heat lag due

TABLE 4  
RELATION BETWEEN ANEMOMETER READING AND TEMPERATURE-RISE

Anemometer Reading Ft. per Min.	Rise in Temperature of Air Degrees F.	Ratio of Anemometer Reading to Temperature-Rise
219	205	1.070
223	215	1.040
223	210	1.062
221	213	1.040
227	221	1.030
231	223	1.040
227	221	1.030
222	215	1.030
Average.....		1.043

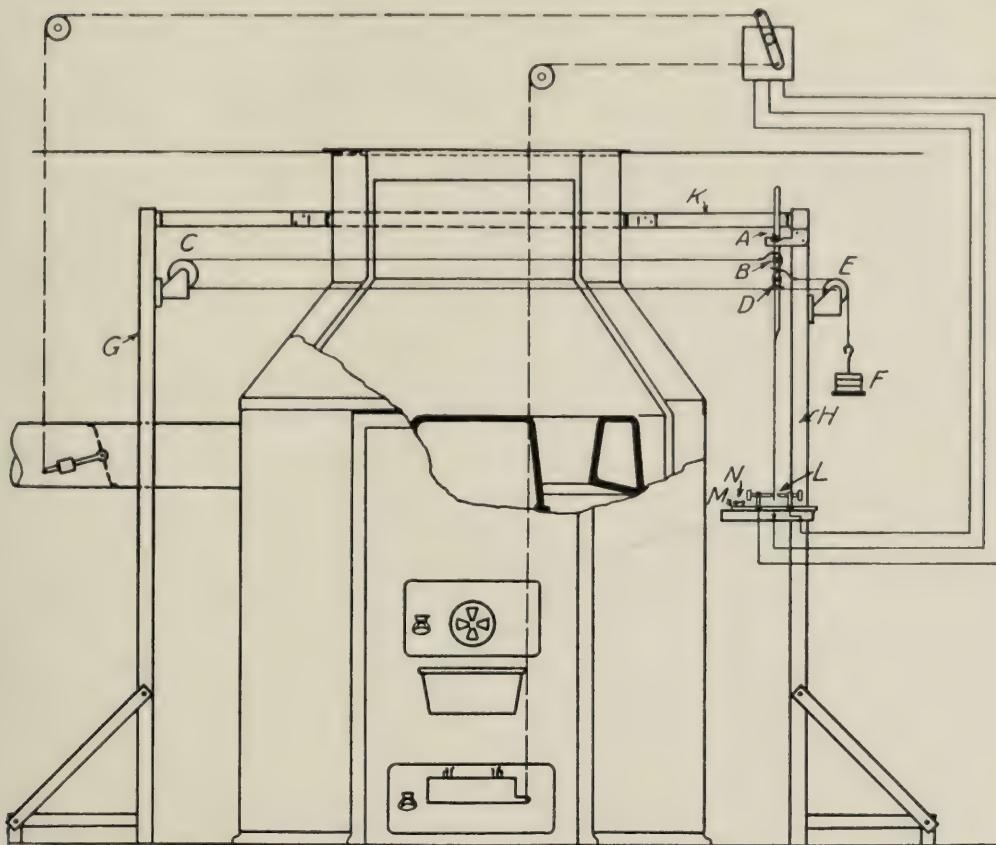


FIG. 16. DRAFT REGULATOR FOR TEMPERATURE CONTROL

to the mass of material used in their construction. A minimum of about 8 or 10 degrees variation in regulation was the best that could be obtained. A special regulator was, therefore, built, which, used in connection with a standard motor driven draft regulator, gave the desired degree of regulation. No claim for commercial utility is made for the expansion element as it is used only in laboratory tests. As shown in Fig. 16 it consists of a No. 30 B. and S. gage brass wire passing through the throat of the furnace, and a lever swinging on knife edges, *A*.

One end of the wire is fastened to the support at the pulley, *E*. The wire then passes through the throat of the furnace, around the pulley at *C*, and back to a yoke which hooks over a knife edge carried on the lever at *B*. The wire is held taut by a set of weights, *F*, the string from which passes over the pulley, *E*, and attaches to the lever by means of a yoke and knife edge at *D*. The weights pull back the lever and thus tighten the wire. Both pulleys and lever system are

supported on heavy members, *G* and *H*, which are entirely free from the furnace or platform and held at a fixed distance by the strut, *K*, (which passes around, and not through, the furnace). The end of the lever oscillates between two contact points at *L*, which are carried on a sliding base, *M*, which may be locked into place by nut, *N*. Leads from the contact points run to the motor which operates the furnace dampers.

The proper position for the contact points for any given temperature-rise is determined by trial, and they are then locked into place by means of the nut, *N*. If the temperature rises, the wire increases in length due to expansion. This allows the lever to be drawn further out, and it makes contact with the outside point at *L*, closing the circuit which operates the motor to close the cross damper in the smoke pipe and the damper in the ash pit door. If the furnace cools, the wire contracts and makes contact with the other point, thus opening the dampers. The No. 30 wire has so little mass that it follows the temperature changes almost instantly, and the furnace can be controlled within the limits desired.

19. *Furnace Testing Codes*.—It has been found very necessary to formulate definite codes for reporting the results of tests on both piped and pipeless furnaces. Such codes must provide for a systematic method of recording all important dimensions and significant constructional details, as well as the observed test data and final results.

After many revisions, the following codes have been found quite satisfactory, and were submitted at the Annual Meeting of the American Society of Heating and Ventilating Engineers, January, 1921, by A. C. Willard and A. P. Kratz in connection with a progress report on the general subject of Furnace Testing.

#### Testing Code for Pipeless Furnaces

Tests under this code may be of two general kinds, depending on the character of the fuel used. For purposes of comparing similar furnaces, or for determining the effect of most changes in design, it has been found satisfactory to use hard coal and run 8 hour tests. The methods for running tests for both hard and soft coal are discussed in Section V.

All tests are so controlled as to require a draft of not more than 0.2 inches of water at any time, and the temperature-rise of the air passing through the furnace is maintained absolutely constant throughout the entire test. Special temperature indicating apparatus is absolutely essential in maintaining a constant temperature-rise. In no case will mercury thermometers be satisfactory for measuring outlet temperatures, because of the serious radiation effects on such thermometers. The temperature control and measuring devices are discussed in Section VI.

The amount of air passing through the furnace is determined by a special traversing equipment (Fig. 12) using an anemometer to measure the velocity of flow. The anemometer is then calibrated under exactly the same conditions of air velocity, temperature, and register resistance as existed in the actual test, as discussed in Section VII.

The observed data and calculated results are then reported on the Data and Result Sheets for Pipeless Furnace Test given on page 56. Fig. 10 shows the general set-up of the equipment for a pipeless furnace test, and also serves as a graphical result sheet. Typical performance curves from a series of tests are shown in Fig. 15.

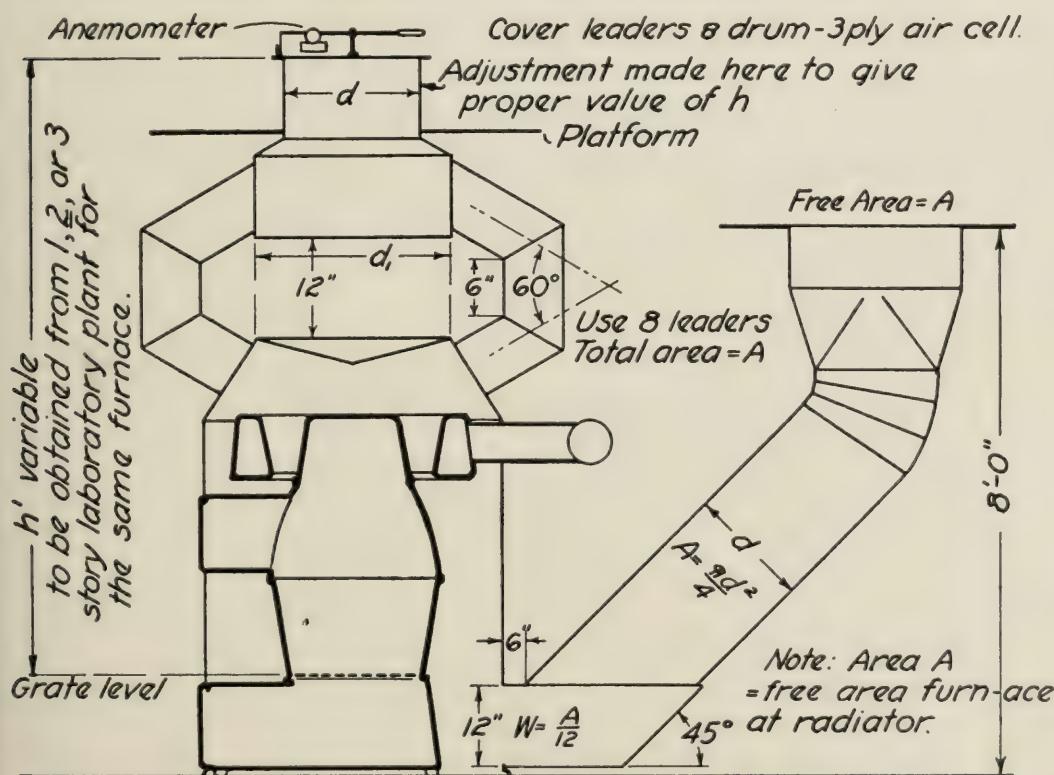


FIG. 17. SECTIONAL ELEVATION OF EQUIVALENT TESTING PLANT FOR PIPED FURNACE

### Testing Code for Piped Furnaces

Tests under this code are made in a manner exactly similar to that already described for pipeless furnaces. The special arrangement of an equivalent piped furnace testing plant is shown in detail in Fig. 17.

The only factor not definitely specified in setting up this equipment is the equivalent head in feet between grate and face of hot air outlet which should be provided.

This head can only be ascertained by setting up a duplicate furnace in a typical one, two, or three-story piped furnace plant and determining the total amount of air handled by natural circulation for an average temperature-rise from inlet to bonnet of 130 deg. F. With this quantity of air known the outlet riser is adjusted to give this same capacity at the same temperature rise. Values for the proper height of the equivalent testing plant (Fig. 17) will depend only on the resistance of the leaders, stacks, and registers in one, two, and three-story plants. Once these heights are determined for systems in one, two, and three-story buildings, the equivalent testing plant will truly represent the actual resistance in such buildings.

The observed data and calculated results are then reported on the Data and Result Sheets for Piped Furnace Test given below. Fig. 17 not only shows the general set-up of the equipment for a piped furnace test, but can also be made to serve as a graphical result sheet similar to Fig. 10 by addition of the necessary items.

Typical performance curves from a series of piped furnace tests are shown in Fig. 6.

#### DATA AND RESULT SHEET—PIPELESS FURNACE TEST

At ..... Date .....

##### GENERAL DATA

Built by ..... Builder's No. ....  
 Type of furnace .....  
 Type of inner and outer casings .....  
 .....  
 Type of grates .....  
 Type of chimney .....  
 Type of register .....  
 Rated capacity .....

## DIMENSIONS

Fire pot diameter at top .....	in., at bottom .....	in.
Grate area .....	sq. ft.	
Diameter of outer casing .....	in.	
Diameter of inner casing, net inside .....	in.	
Thickness of inner casing .....	in.	
Diameter of radiator .....	in.	
Distance from outside of radiator to inner casing .....	in.	
Distance between inner and outer casing .....	in.	
Distance from floor to bottom of inner casing .....	in.	
Least free area across inner casing .....	sq. in.,.....	sq. ft.
Least free area between inner and outer casing .....	sq. in.,.....	sq. ft.
Ratio of cold air free area to hot air free area .....	.....	
Throat diameter below register, net .....	in.	
Width and length of cold-air register .....	x.....	in.
Net free area of cold-air register .....	sq. in.....	sq. ft.
Diameter of hot-air register .....	.....	in.
Net free area of hot-air register.....	sq. in.,.....	sq. ft.
Ratio free area to gross area of register.....	cold-air.....	hot-air.....
Ratio free area of cold-air to free area of hot-air register .....	.....	
Diameter and length of smoke pipe .....	in. x .....	ft.
Size and height of chimney .....	in. x .....	ft.

No. *Name of Item with Units*

1. Duration of test, hours.....	.....	.....
2. Barometer, in. of mercury .....	.....	.....
3. Kind of coal .....	.....	.....
4. Size of coal .....	.....	.....
5. Proximate analysis of coal as fired, per cent .....	.....	.....
6. Fixed carbon .....	.....	.....
7. Volatile matter .....	.....	.....
8. Moisture .....	.....	.....
9. Ash .....	.....	.....
10. Sulphur, separately determined .....	.....	.....
11. Calorific value of coal as fired, by oxygen calorimeter, B.t.u. per lb. .....	.....	.....
12. Ultimate analysis of coal as fired, per cent .....	.....	.....
13. Carbon .....	.....	.....
14. Hydrogen .....	.....	.....
15. Oxygen .....	.....	.....
16. Nitrogen .....	.....	.....
17. Sulphur .....	.....	.....
18. Moisture .....	.....	.....
19. Ash .....	.....	.....
20. Analysis of dry refuse at end of test, per cent .....	.....	.....
21. Fixed carbon .....	.....	.....

22.	Volatile matter .....	.....
23.	Earthy matter .....	.....
24.	Calorific value, B.t.u. per lb. ....	.....
25.	Draft at smoke outlet, in. of water .....	.....
26.	Temperature of outside air, deg. fahr.....	.....
27.	Temperature of air entering ash pit, deg. fahr.....	.....
28.	Temperature of inlet air at register face, dry bulb, deg. fahr.....	.....
29.	Temperature of inlet air at register face, wet bulb, deg. fahr.....	.....
30.	Temperature of outlet air at register face, deg. fahr.....	.....
31.	Temperature rise of air from inlet to outlet, deg. fahr.....	.....
32.	Equivalent outlet temperature at register face above 65 deg. fahr. ....	.....
33.	Temperature of cold air 2 in. above bottom of inner casing, deg. fahr. ....	.....
34.	Temperature of outer casing opposite center of fire pot, deg. fahr .....	.....
35.	Temperature of outer casing 6 in. above floor, deg. fahr.....	.....
36.	Temperature of flue gas, deg. fahr. ....	.....
37.	Velocity through free area of outlet register, ft. per min...	.....
38.	Velocity through minimum free area of furnace, ft. per min.....	.....
39.	Velocity through minimum free area of outer casing, ft. per min. ....	.....
40.	Velocity through free area of inlet register, ft. per min.....	.....
41.	Volume of air leaving hot-air register, measured at the actual register temperature, cu. ft. per hour.....	.....
42.	Volume of air leaving hot-air register, measured at the equivalent register temperature, cu. ft. per hour.....	.....
43.	Density of air entering cold-air register, lb. per cu. ft.....	.....
44.	Density of air leaving hot-air register, lb. per cu. ft.....	.....
45.	Weight of air circulated per hour, lb.....	.....
46.	Weight of air circulated per lb. of coal burned, lb.....	.....
47.	Weight of air circulated per 10 000 B.t.u. supplied in coal, lb.	.....
48.	Weight of coal fired, total, lb. ....	.....
49.	Weight of dry refuse at end of test, total, lb.....	.....
50.	Weight of equivalent coal in refuse, lb.....	.....
51.	Net weight of coal burned during test, lb.....	.....
52.	Combustion rate, lb. of coal burned per sq. ft. of grate per hour .....	.....
53.	Heat developed by net coal burned per hour, B.t.u.....	.....
54.	Heat put into air between inlet and outlet per hour, B.t.u..	.....
55.	Heat available above 70 deg. fahr. for heating house per hour, B.t.u. .....	.....
56.	Heat put into air between inlet register and bottom of inner casing per hour, B.t.u.....	.....
57.	Total heat put into air which is transmitted by inner casing to entering air, per cent .....	.....
58.	Overall efficiency of furnace, per cent .....	.....

59. Carbon dioxide in flue gas, per cent .....

60. Oxygen in flue gas, per cent .....

61. Heat lost in flue gas per lb. of coal burned, B.t.u. ....

62. Heat lost by radiation and "unaccounted for" per lb. of coal  
burned, B.t.u. ....

63. Heat lost in flue gas, per cent .....

64. Heat lost by radiation and "unaccounted for," per cent .....

*Remarks:*

.....  
.....  
.....

## DATA AND RESULT SHEET—PIPED FURNACE TEST

At ..... Date .....

## GENERAL DATA

Built by ..... / Builder's No. ....

Type of furnace .....

Type of outer casing .....

Type of lining .....

Type of grates .....

Type of chimney .....

Number of leaders .....

Rated capacity .....

## DIMENSIONS

Fire pot diameter at top ..... in., at bottom ..... in.

Grate area ..... sq. ft.

Diameter of outer casing ..... in.

Diameter of lining, net inside ..... in.

Thickness of lining ..... in.

Diameter of radiator ..... in.

Distance from outside of radiator to lining ..... in.

Diameter of cold-air duct ..... in.

Height of cold-air shoe ..... in., and width ..... in.

Least free area across inner casing ..... sq. in. .... sq. ft.

Ratio of cold-air free area to total hot-air leader area .....

Throat diameter of outlet ..... in.

Width and length of cold-air register ..... x ..... in.

Net free area of cold-air register ..... sq. in. .... sq. ft.

Ratio free area to gross area of cold-air register .....

Diameter of top of bonnet ..... in.

Diameter of leaders ..... in.

Total area of leaders ..... sq. in. .... sq. ft.

Diameter of bottom of drum ..... in.

Height from grate to face of hot-air outlet ..... ft. .... in.  
 Diameter and length of smoke pipe ..... in. .... ft.  
 Size and height of chimney ..... in. .... ft.

No.                    Name of Item with Units

1.	Duration of test, hours	.....	.....
2.	Barometer, inches of mercury	.....	.....
3.	Kind of coal	.....	.....
4.	Size of coal	.....	.....
5.	Proximate analysis of coal as fired, per cent	.....	.....
6.	Fixed carbon	.....	.....
7.	Volatile matter	.....	.....
8.	Moisture	.....	.....
9.	Ash	.....	.....
10.	Sulphur, separately determined	.....	.....
11.	Calorific value of coal as fired, by oxygen calorimeter, B.t.u. per lb.	.....	.....
12.	Ultimate analysis of coal as fired, per cent	.....	.....
13.	Carbon	.....	.....
14.	Hydrogen	.....	.....
15.	Oxygen	.....	.....
16.	Nitrogen	.....	.....
17.	Sulphur	.....	.....
18.	Moisture	.....	.....
19.	Ash	.....	.....
20.	Analysis of dry refuse at end of test, per cent	.....	.....
21.	Fixed carbon	.....	.....
22.	Volatile matter	.....	.....
23.	Earthy matter	.....	.....
24.	Calorific value, B.t.u. per lb.	.....	.....
25.	Draft at smoke outlet, in. of water	.....	.....
26.	Temperature of outside air, deg. fahr.	.....	.....
27.	Temperature of air entering ash pit, deg. fahr.	.....	.....
28.	Temperature of inlet air at register face, dry bulb, deg. fahr.	.....	.....
29.	Temperature of inlet air at register face, wet bulb, deg. fahr.	.....	.....
30.	Temperature of outlet air at face of hot-air outlet, deg. fahr.	.....	.....
31.	Temperature of air at bonnet, deg. fahr.	.....	.....
32.	Temperature rise of air from inlet to bonnet, deg. fahr.	.....	.....
33.	Equivalent outlet temperature at register faces above 65 deg. inlet, deg. fahr. allowing ..... deg. fahr. drop in leaders and stacks	.....	.....
34.	Temperature of outer casing opposite center of fire pot, deg. fahr.	.....	.....
35.	Temperature of outer casing 6 in. above floor, deg. fahr.	.....	.....
36.	Temperature of flue gas, deg. fahr.	.....	.....
37.	Velocity through free area of outlet, ft. per min.	.....	.....
38.	Velocity through minimum free area of furnace, ft. per min.	.....	.....

39. Velocity through cold air duct, ft. per min.....	.....
40. Velocity through free area of inlet register, ft. per min.....	.....
41. Volume of air leaving hot-air outlet, measured at the actual outlet temperature, cu. ft. per hour .....	.....
42. Volume of air leaving hot-air register, measured at the equivalent register temperature, cu. ft. per hour...	.....
(Note:—See item 33.)	
43. Density of air entering cold-air register, lb. per cu. ft.....	.....
44. Density of air leaving hot-air outlet, lb. per cu. ft. ....	.....
45. Weight of air circulated per hour, lb.....	.....
46. Weight of air circulated per lb. of coal burned, lb.....	.....
47. Weight of air circulated per 10,000 B.t.u. supplied in coal, lb.	.....
48. Weight of coal fired, total, lb. ....	.....
49. Weight of dry refuse at end of test, total, lb.....	.....
50. Weight of equivalent coal in refuse, lb.....	.....
51. Net weight of coal burned during test, lb.....	.....
52. Combustion rate, lb. of coal burned per sq. ft. of grate per hour .....	.....
53. Heat developed by net coal burned per hour, B.t.u.....	.....
54. Heat put into air between inlet and bennet per hour, B.t.u...	.....
55. Heat available above 70 deg. fahr. for heating house per hour, B.t.u. ....	.....
(Note:—See item 33.)	
56. Overall efficiency of furnace, per cent .....	.....
(Note:—Based on bonnet temperature.)	
57. Carbon dioxide in flue gas, per cent .....	.....
58. Oxygen in flue gas, per cent .....	.....
59. Heat lost in flue gas per lb. of coal burned, B.t.u. ....	.....
60. Heat lost by radiation and "unaccounted for" per lb. of coal burned, B.t.u. ....	.....
61. Heat lost in flue gas, per cent .....	.....
62. Heat lost by radiation and "unaccounted for," per cent .....	.....

*Remarks:*

.....  
.....  
.....

## VI. TEMPERATURE MEASUREMENT IN WARM-AIR FURNACE TESTING

20. *Measurement of Outlet Temperatures.*—It is a very difficult matter to determine accurately the temperature of the air as it leaves the bonnet of a piped furnace, or as it passes the register grille of a pipeless furnace. Attempts to measure air temperatures at these points by ordinary thermometers are futile, since the errors resulting from the radiation effect of the hot dome and radiator of the furnace may amount to from 40 deg. to 90 deg. F., as was demonstrated in this investigation. Even with very small thermocouples there is an error from this radiation effect, but the error is much less than with thermometers, and has now been accurately determined. Since the problems are about the same for both piped and pipeless plants, a discussion of the method used in the latter tests will suffice for both. It should be noted that mercury thermometers are quite satisfactory for measuring inlet temperatures for either piped or pipeless furnaces, as there are practically no radiation effects at such points.

21. *Instruments Used for Measuring Temperature.—***Thermocouples**

The temperature of the air at the register face was measured by means of four copper-constantan thermocouples made of No. 23 B. and S. gage wire. A general discussion of the thermocouple method of measuring temperatures and the factors leading to the choice of copper-constantan couples has been given in a previous bulletin.\*

The junctions of the couples used for this purpose were formed by silver-soldering the two wires together and dressing the metal down to approximately the diameter of the wires. These junctions were placed at 90 degrees around a circle having a radius of about 0.6 that of the register face. The four couples were then connected in parallel and a single reading gave the average of the temperature at the four points. In the earlier tests an instrument called the Pyrovolter was used, which gave a precision of 0.42 deg. F. For the

\* "Report of Progress in Warm-Air Furnace Research." Univ. of Ill. Eng. Exp. Sta., Bul. 112, 1919.

later tests a standard Leeds and Northrup precision potentiometer was used. This could be read accurately to 0.0005 millivolts, which gave a possible precision of 0.02 deg. F. For the purpose of these tests, however, it was not used to a greater precision than 0.2 deg. F., which was considered ample.

A discussion of the essential differences between a Pyrovolter and a potentiometer as measuring instruments may be of interest for other investigators in this field, and is given in the following paragraphs.

### Potentiometer

In the simplest form the potentiometer (Fig. 18) consists of a loop of wire, a bull cell,  $B$ , and a variable resistance. One portion of the loop is a very uniform wire,  $X-Y$ , lying adjacent to a scale. Suppose this scale contains 10 main divisions. The fall of potential,  $E$ , from  $X-Y$  is then  $E = IR$ , where  $E$  is electromotive force,  $I$  is current, and  $R$  is ohms resistance. Then each division of the wire  $= \frac{E}{10}$ , or if  $E = 10$  volts then each division  $= 1$  volt.

In order to make the instrument direct reading it is necessary to determine what current in the loop will make each division represent 1 volt. Suppose a standard cell of known voltage,

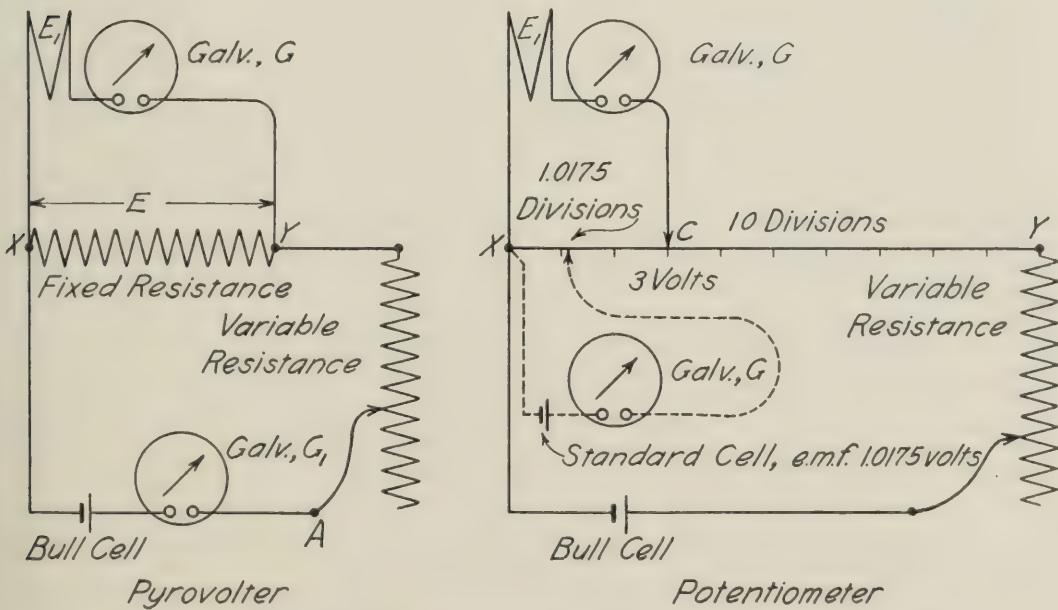


FIG. 18. DIAGRAMS FOR PYROVOLTER AND POTENTIOMETER CIRCUITS

$E = 1.0175$ , is connected with one pole at point  $X$  and the second pole at a distance of 1.0175 divisions from point  $X$  in such a way that the fall of potential along the wire from  $X$  to 1.0175 tends to send current in one direction through the galvanometer and the cell tends to send it in the other direction. The current,  $I$ , in the loop is now changed until the fall along the wire from point  $X$  to 1.0175 is just 1.0175 volts. This is true when the galvanometer reads zero. In this case every division on the wire will represent a fall of potential of just 1 volt.

$I$  is now maintained constant in the loop, and an unknown electromotive force,  $E_1$ , is connected in just as the standard cell was connected. Assume that the electromotive force is 3 volts. If the point  $C$  is placed on the third division it is evident that the fall of potential from  $X$  to  $C$  will be 3 volts. In this case the galvanometer will read zero. If  $C$  is placed on either side of 3, then the galvanometer will read either positive or negative as the case may be. Hence the length of wire from  $X$  to  $C$  may be made a measure of the unknown electromotive force, since each division was first adjusted to represent a known fall in potential and the current  $I$  was not afterwards changed.

#### Pyrovoltmeter

The unknown electromotive force,  $E_1$ , is connected across the fixed resistance  $X-Y$ , as shown in Fig. 18. The fall of potential across this fixed resistance is  $E = IR$ , where  $R$  is the resistance  $X-Y$ , and  $I$  is the total current in the loop,  $XAYX$ . If  $I$  is varied, then  $E$  will vary also. The unknown electromotive force,  $E_1$ , is so connected that it opposes  $E$ , and when  $E$  is just equal to the unknown  $E_1$  the galvanometer  $G$  will read zero, since there is no current flowing through it.  $I$  is varied by the variable resistance in the loop until  $G$  does read zero; then the relationship  $E = E_1$  is true.  $I$  is then read on galvanometer  $G_1$ . But since  $I = E/R$ , and  $R$  is constant and known, the galvanometer  $G_1$  may be calibrated to read  $E$  directly for the different values of  $I$  which are necessary to balance various unknown electromotive forces  $E_1$ , or in other words may be calibrated to read  $E_1$  directly for the different values of  $I$ .

In Fig. 19 there is given a diagram of the method of calibration and a typical calibration curve for a copper-constantan couple. In making a calibration, the junction of the couple is bound to the bulb of a standard mercury thermometer the correctness of which has

been certified by the United States Bureau of Standards. The thermometer and couple are then immersed in an electrically heated oil bath and simultaneous readings are taken of the thermometer and Pyrovoltmeter, or potentiometer, as the case may be. The electromotive forces read from the potentiometer are then plotted as abscissae and the temperatures from the mercury thermometer as ordinates. Thereafter, if the couple is used and gives, for instance, a reading of 3.0 millivolts the corresponding temperature of 164 deg. F. may be obtained from the curve, as indicated by the dotted lines shown in Fig. 19.

#### Temperature-Rise Indicator

For the laboratory tests, it has been found convenient to observe the constancy of the temperature-rise from the readings of the compound couple at the register face as discussed in the preceding paragraphs. The potentiometer dials are set at the reading which

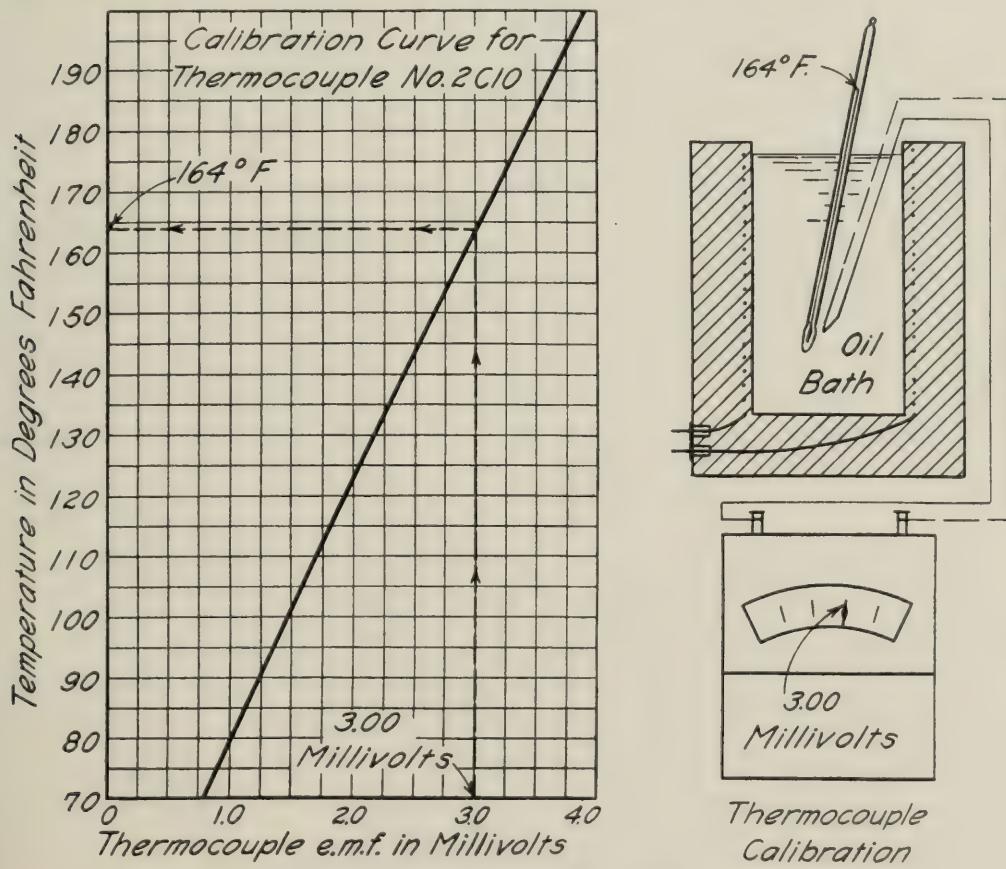


FIG. 19. THERMOCOUPLE CALIBRATION CURVE AND APPARATUS

gives the temperature at register face required to give the desired rise in temperature. Any deviation from this temperature is immediately indicated by the swing of the galvanometer.

For work in the field, however, a special temperature-rise indicator has been developed. A Pyrovolter and eight copper-constantan thermocouples made of No. 23 B. and S. gage wire connected in series are used. The electrical connections, including the wiring diagram for the Pyrovolter, are shown in Fig. 20. In this figure only two couples are shown in series instead of the eight which are actually used. The compound thermocouple is placed in the throat of the furnace with the hot junction spread out fanlike at *A*. The cold junctions, *B*, are placed outside of the throat and in the air surrounding the furnace.

The readings of this compound couple, therefore, indicate temperature-rise directly. They are not used for the recorded air temperature, however, a calibrated couple with the cold junction in ice being used for this purpose. The indicator couple is connected through a double pole switch, *S*, across the fixed resistance,  $R_1$ , with the galvanometer,  $G_2$ , in the circuit. The Pyrovolter circuit contains this fixed resistance,  $R_1$ , variable resistance,  $R_2$ , galvanometer,  $G_1$ , and a dry cell, or two dry cells in series, *C*.

In order to adjust the indicator, the furnace is first operated to give the desired temperature-rise. Switch *S* is then closed, and the variable resistance  $R_2$  is adjusted until galvanometer  $G_2$  reads zero. The reading of galvanometer  $G_1$  is noted, and whenever this same temperature-rise is desired  $G_1$  must be set to this predetermined reading. With  $G_1$  set, then  $G_2$  will read zero as long as the correct temperature-rise is being maintained. Any variation in the tempera-

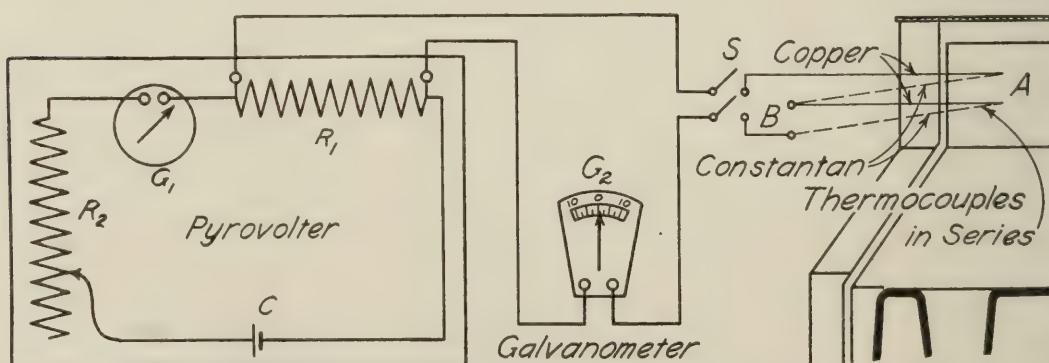


FIG. 20. AIR TEMPERATURE-RISE INDICATOR FOR FURNACE TESTING

ture-rise will be indicated by deflection of the galvanometer  $G_2$ . With the instrument used, a change of 10 degrees in the temperature rise produced a deflection of about  $5/16$  inch on the galvanometer.

22. *Correction for Radiation.*—Since the efficiencies reported for either the piped or pipeless furnace are based on the temperature rise of the air passing through the furnace, it becomes a matter of prime importance that an accurate method for the determination of the temperature of the air leaving the register face be used. The chief difficulty encountered in these tests was the determination of, and the correction for, the effect of the heat radiated from the hot castings on the thermometers or thermocouples used to measure the air temperature. It was necessary to measure this temperature at a point either just below the bonnet or close to the register face. This exposed the measuring element directly to the radiant heat given off from the top of the dome and the radiator. Since these castings were at a temperature considerably higher than that of the air, and the radiant heat went directly through the air without warming it, the effect was to raise the thermal element of the thermometer or thermocouple that received this heat to a higher temperature than that of the air surrounding it. Consequently, since the material of which the thermal element was constituted was at a higher temperature than that of the air the instrument also read or recorded a higher temperature than the true air temperature. This observed temperature proved to be as much as 90 deg. F. too high (see Fig. 23) when a mercury thermometer was used. The error could not be eliminated by interposing shields or baffles between the hot surfaces and the thermometer, because the shields would merely intercept the radiation and become heated, and in turn radiate to the thermometer. The only course left open, therefore, was to correct for the radiation effect on these couples.

The radiation correction has been made as suggested\* by Henry Kreisinger and J. F. Barkley. Four thermocouples having diameters of 0.01 inch, 0.0225 inch, 0.065 inch, and 0.129 inch, respectively, were placed at the point at which measurements were to be taken for the tests. The junctions were carefully made of the same diameter as the wires forming the couples. Since the larger surfaces received

\* "Measuring the Temperature of Gases in Boiler Settings." U. S. Bureau of Mines, Bulletin 145.

more heat by radiation than the smaller ones, the temperature indicated by the larger couples when equilibrium was attained was correspondingly higher than that indicated by the smaller ones. The smaller couples gave more nearly the correct air temperature. Theoretically, a couple of zero diameter would give the correct air temperature, since a couple of this diameter would receive no heat by radiation. The temperatures indicated by the four couples were then plotted against the diameter of the wires forming the couples. A smooth curve joining these points was drawn and continued until it intersected the zero diameter axis. The point where this took place was regarded as indicating the true temperature of the air. These curves are shown in Fig. 21. One of these curves, it may be seen, intersects the zero axis at 298 deg. F. This is the true air temperature. The couple of 0.0225 inch diameter, which was the size of the couples used to measure the temperature during the tests, at the same time read 320 deg. F. The correction for this couple is, therefore,  $320 - 298 = 22$  deg. F. This procedure was followed for a large number of temperatures within the range covered by the tests on the pipeless furnace, and the corrections obtained have been plotted against the observed temperatures. The correction curve is shown in Fig. 22 and has been used on all pipeless furnace tests herein reported. It must be noted that this correction curve applies only to couples of the diameter designated, and then only when the couples are placed at the same distance from the dome of the furnace, namely, 36 inches.

In order to call attention to the magnitude of the errors that might occur from the use of an unprotected mercury thermometer, a correction curve for a mercury thermometer having a diameter of 0.225 inches and placed 36 inches above the dome is given in Fig. 23. The corrections vary from 40 deg. F. at an observed register temperature of 200 deg. F. to 90 deg. F. at an observed register temperature of 300 deg. F.

In Fig. 24 is shown a radiation correction curve for couples of No. 23 B. and S. gage wire placed in the bonnet of a piped furnace. These couples were placed at the entrance to the leaders, and about 9 inches from the radiator castings. The correction in this case is 10 deg. F. at an observed temperature of 197 deg. F. The corresponding correction at 197 deg. F. taken from the curve in Fig. 22 for the pipeless furnace is 9.5 deg. F. At 223 deg. F. the correction is 13 deg. which also very closely agrees with the correction of 12 deg.

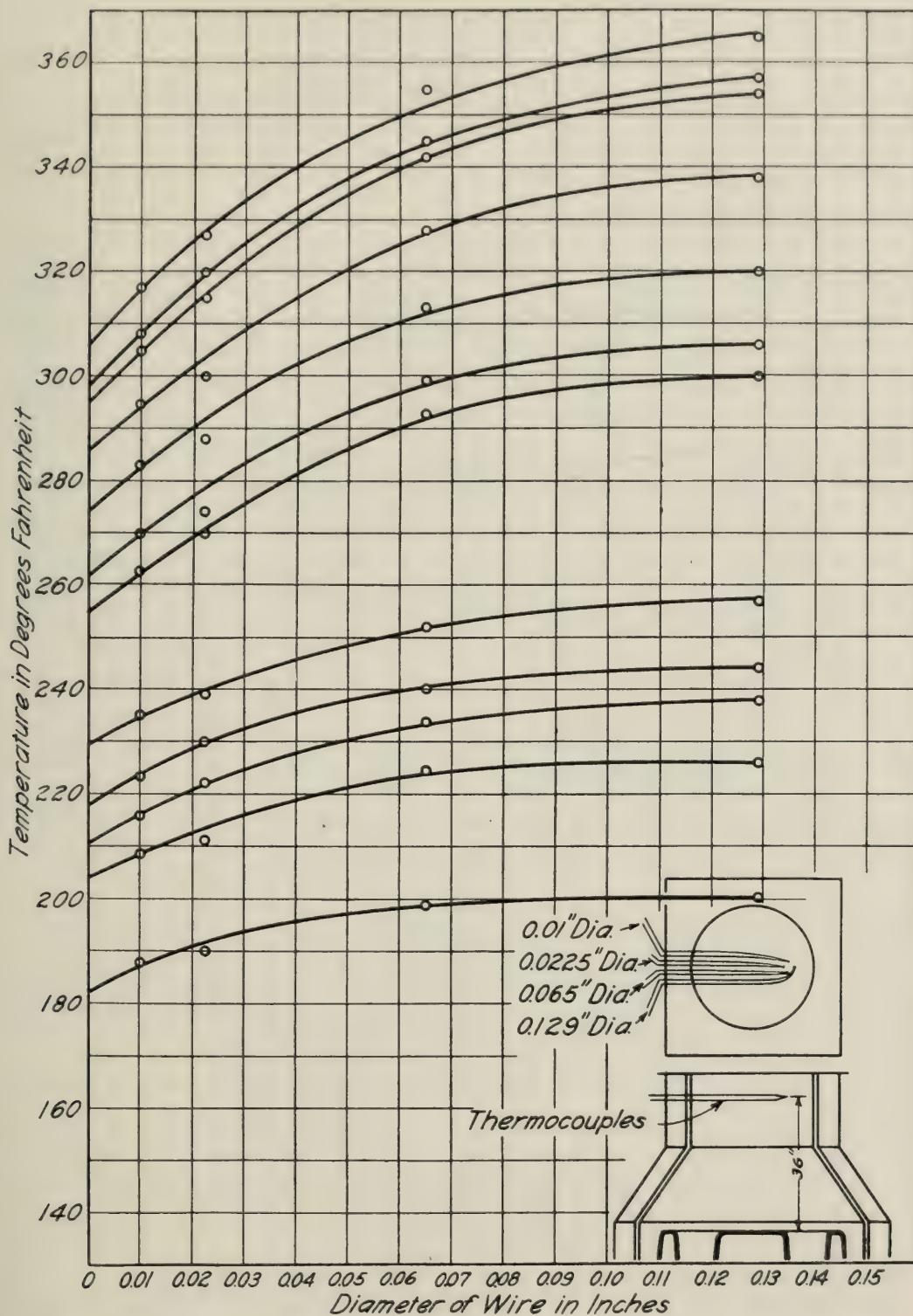


FIG. 21. EFFECT OF RADIATION ON THERMOCOUPLES, FOR PIPELESS FURNACE

taken from the correction curve for the pipeless furnace. It appears, in this particular case, that the distance the couple is placed from the castings does not materially affect the correction, and that the curves for the pipeless furnace may be accepted for the piped furnace also without very great error.

23. *Temperature of Furnace Castings.*—The temperature of the furnace castings has been observed at several points on the pipeless furnace. These temperatures were obtained by the use of chromel-alumel thermocouples made from No. 23 B. and S. gage wire. The two wires were twisted tightly together and the junction thus formed was fused in an oxy-gas flame. A small hole was then drilled into the casting, the junction inserted and the hole peened shut with a cold chisel. In some cases, where the casting was too hard to permit peening, the couple was packed into the hole by driving asbestos cord into the hole with it. No attempt was made to obtain the temperature of the surface alone. The temperature obtained was that of the metal.

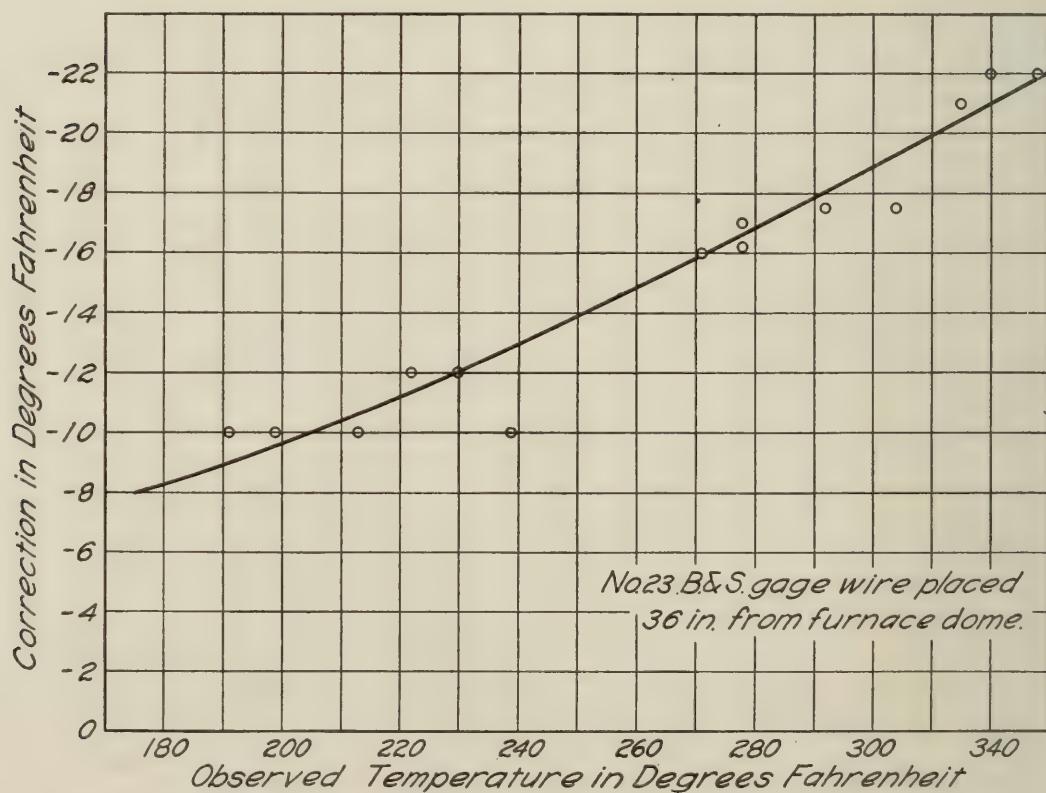


FIG. 22. RADIATION CORRECTION CURVES FOR THERMOCOUPLES AT REGISTER OF PIPELESS FURNACE

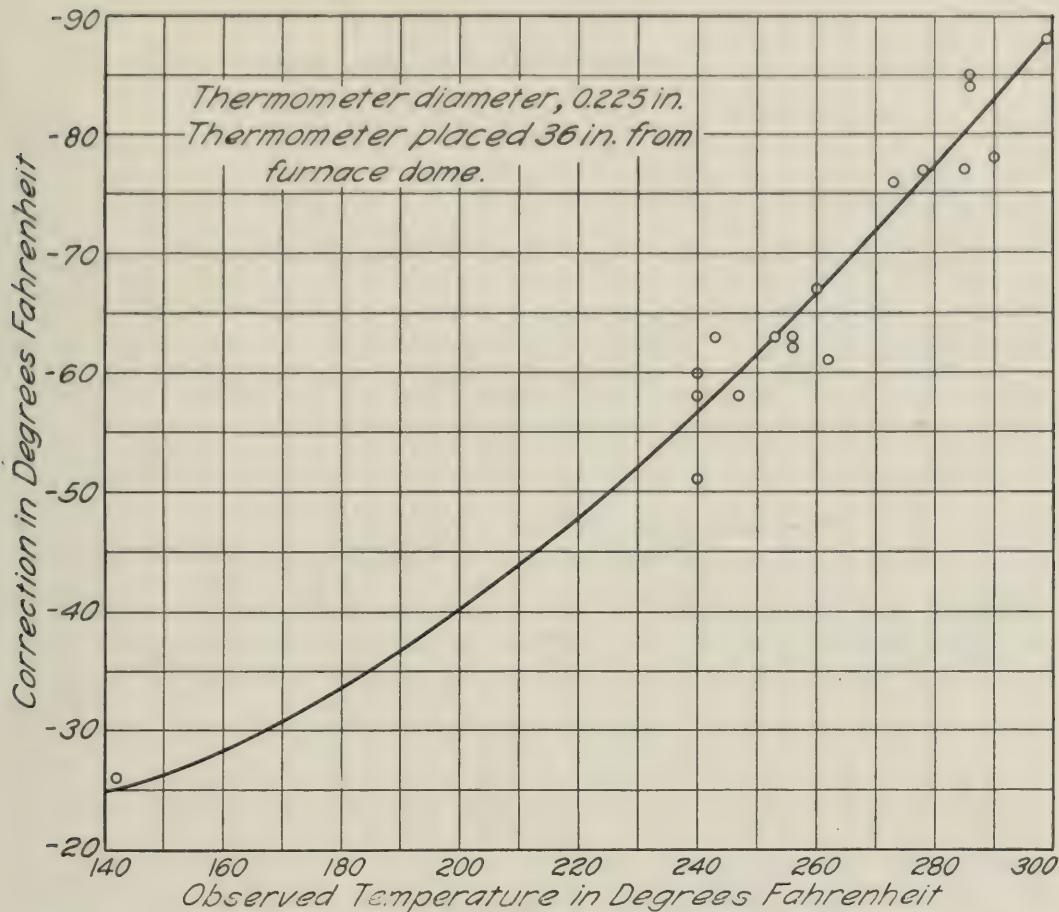


FIG. 23. RADIATION CORRECTION CURVE FOR THERMOMETER AT REGISTER OF PIPELESS FURNACE

The location of these couples was as shown in Fig. 25. One was placed on the side of the fire pot 9 inches above the grate, one on the opposite side of the fire pot 10 inches above the grate, one in the center of the top surface of the dome, one in the top surface of the radiator where the gases made the first turn, and one in the top of the radiator where the gases turned into the smoke connection. The two couples last mentioned were located on the center line of the radiator and above the center of the connections from the dome to the radiator and from the radiator to the smoke connection. The temperatures obtained are discussed in Section XII.

Temperatures on the sheet metal casings and the furnace front were obtained by fastening the bulbs of mercury thermometers to the surfaces by means of furnace cement.

24. *Temperature Variation Across an Air Stream.*—There is still another aspect to this measurement of the temperature of a flowing stream of air which has been given a great deal of study. It is a well known fact that there is a great variation in temperature across any section of an air stream whether the air current is flowing in a nearly horizontal leader or in a vertical stack. The exact location of the thermocouple in such a stream is a matter of vital importance, especially if this reading is to be compared with another reading further along the stack or leader. As a preliminary study with rather crude apparatus showed a surprising variation in an ordinary leader, it was decided to go into the matter more thoroughly, and a special temperature searching tube under micrometer control was developed and put into operation with great success. A few sample curves are submitted (Fig. 26) which speak for themselves. Both temperature traverses were made in the same 10-in. pipe just 5 ft. from the bonnet on the auxiliary plant (Fig. 50) and at the same section taken along a vertical diameter. The bonnet and room temperatures were the

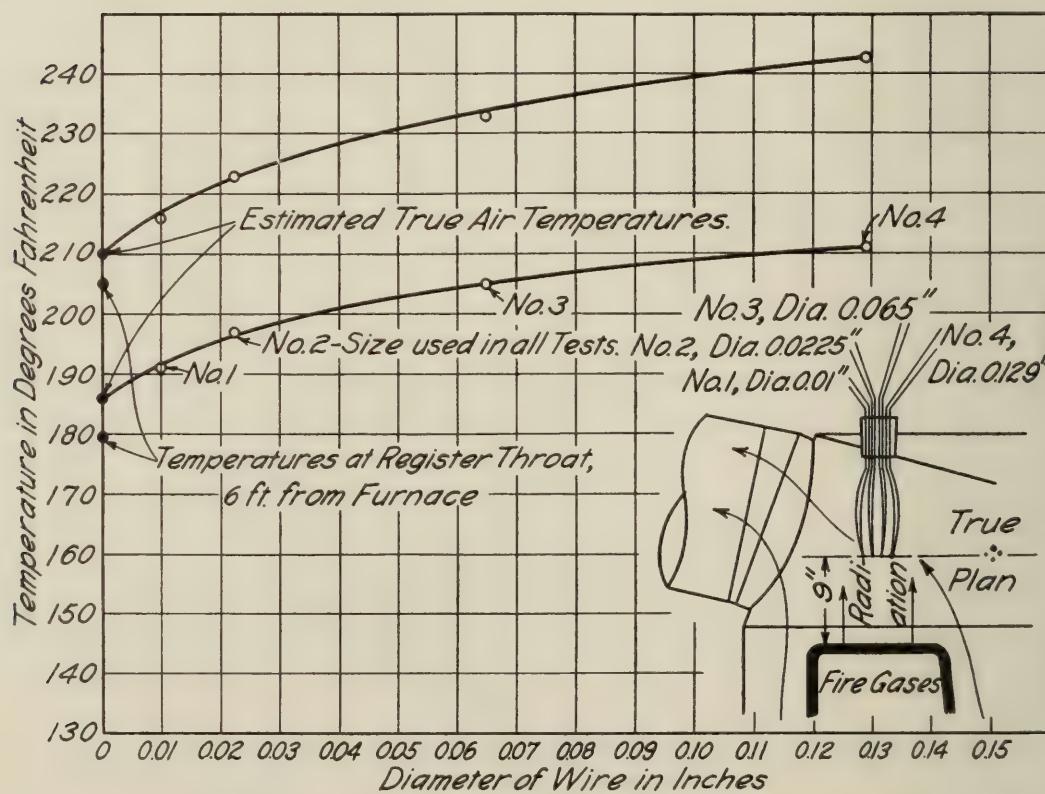


FIG. 24. EFFECT OF RADIATION ON THERMOCOUPLES IN BONNET OF PIPED FURNACE

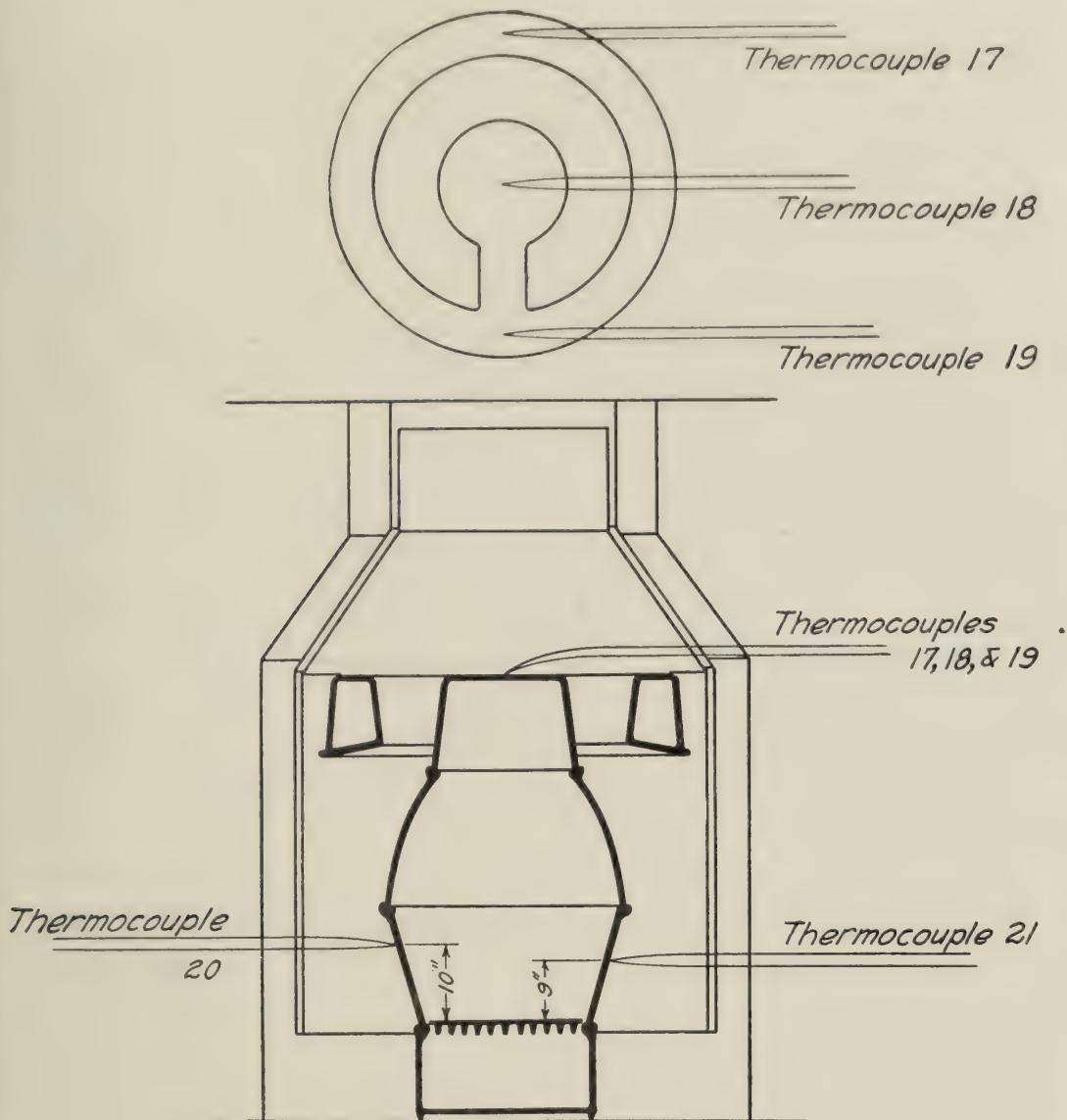


FIG. 25. LOCATION OF THERMOCOUPLES ON FURNACE CASTINGS

same in both cases, and hence the curves are a direct index of the increased heat and air carrying capacity of a bright tin leader pipe as compared with the same pipe covered with one layer of asbestos paper, weighing 10 lb. to the 100 sq. ft.

From an inspection of the curves it is apparent that in the case of the bright tin leader the maximum air temperature at the section was 181.5 deg. F. at a point 2 in. below top of pipe. These temperatures fell off rapidly to 154 deg. F. at a distance 0.01 in. inside of top of pipe, while the temperature of the metal surface itself (by

thermocouple soldered to outside of leader) was 132 deg. F. Below the center of the pipe the air temperatures also fell off rapidly to 130 deg. F. at a distance 0.01 in. inside of bottom of pipe, while the metal surface here was at a temperature of 116 deg. F. The temperature curve for the asbestos covered pipe is similar, but while its maximum is 178 deg. F. at 2 in. below top of pipe or 3.5 deg. F. less than for the bright tin leader at the same position, the metal surface at top and bottom of leader was nearly 9 deg. F. less at the top and 6 deg. F. less at the bottom than the metal surface of the uncovered leader. *The asbestos-paper-covered pipe was losing heat more rapidly than the bright tin leader pipe.*

It therefore becomes a nice question to determine the heat content of the air at any given section and compare it with the heat content at some other section. This problem is still further complicated by the fact that a velocity traverse at this same section (Fig. 27) with a Pitot tube and micromanometer shows a somewhat similar variation in uniformity of flow across the section. The true mass temperature is then the summation of the products of the weight of air at each concentric equal area  $a, b, c, d$ , and  $e$  and the mean temperature at that concentric area (Fig. 27), divided by the total weight of air flowing.

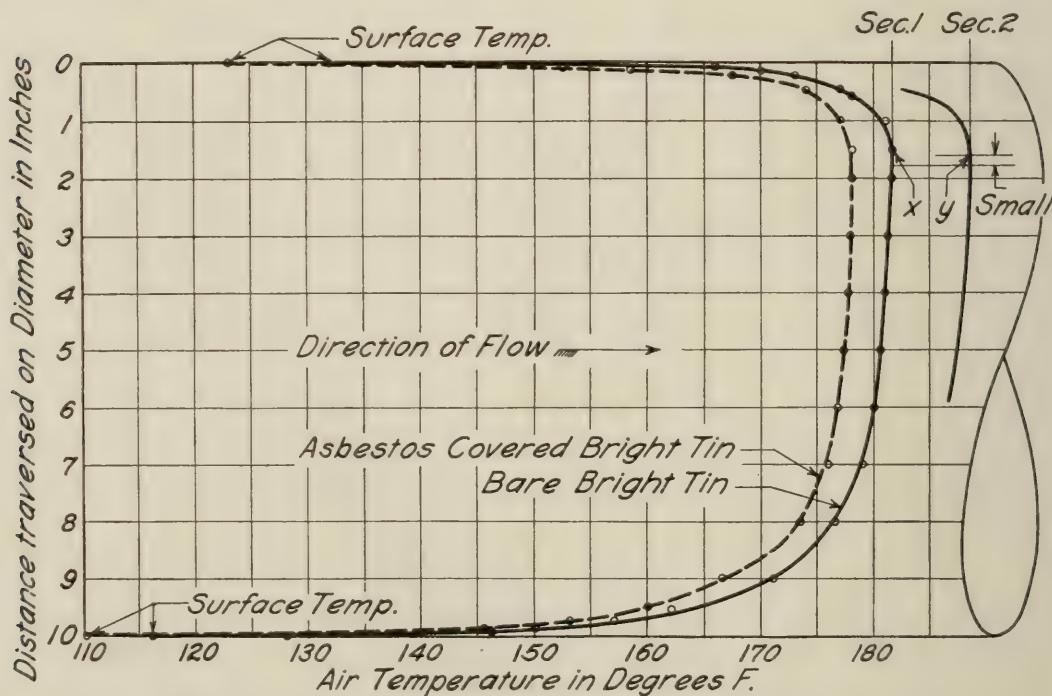


FIG. 26. TEMPERATURE TRAVERSE OF A 10-INCH LEADER

So long as the temperature traverse curve at one section has the same shape as at another section, and the velocity traverse curves are similar to each other, *differences in temperature and heat content* are quite correctly obtained if the thermocouples are located at similar points as indicated by the temperature curves at the two sections. See *x* and *y* at two sections on Fig. 26.

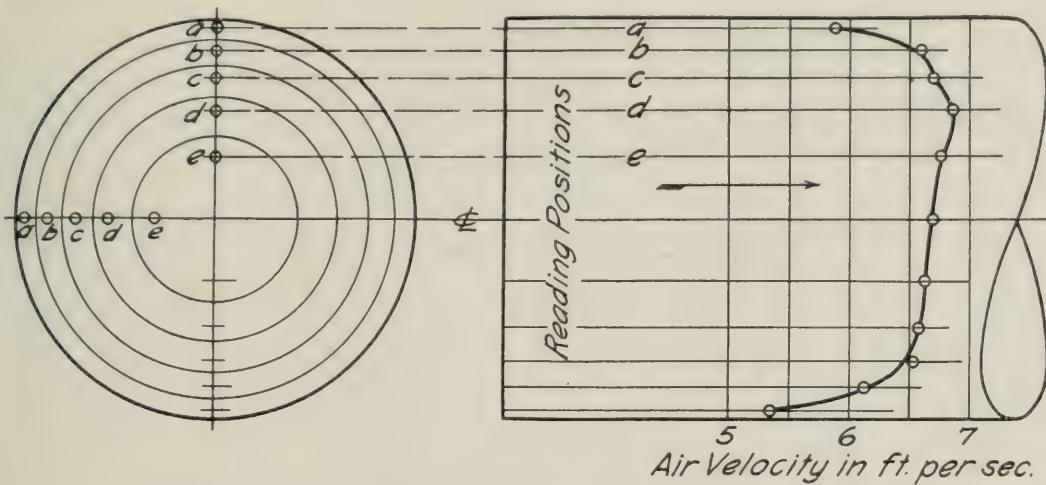


FIG. 27. VARIATION IN VELOCITY ACROSS A 10-INCH LEADER

## VII. AIR MEASUREMENT IN FURNACE TESTING

25. *Direct and Indirect Methods.*—The measurement of the air flow in furnace testing offers peculiar difficulties owing to the low velocities encountered and the very small pressure differences which cause the flow. The small pressure differences, or operating heads, render it impossible to make use of direct measuring devices similar to the Thomas meter, or other meters, due to the fact that such meters impose resistance greater than the available operating heads. The development of the Wahlen gage (Section IX) has made it possible to extend the range of the Pitot tube to velocities below 500 feet per minute, which had previously been considered the lower limit for the use of the tube. However, the necessity for extreme refinement in the measurements of velocity head, and the time consumed in making traverses with the Pitot tube, make the use of this method unsatisfactory where a large number of observations are required, as in furnace testing work. For this reason it was decided to use the anemometer as an indicating instrument, and methods were devised for comparing and checking the readings of the anemometer against some primary apparatus for accurately measuring the amount of air flowing. This comparison must, of course, be made under the same conditions as existed when the original observations were made on the furnace plants.

26. *Method for a Piped Furnace Test.*—A discussion of a general scheme for traversing the register faces and checking the anemometer readings for the piped furnace is given in the first report of progress.\* The primary methods for measuring air for this work have been further developed and will be discussed in a later paragraph, but the general scheme as originally outlined has been retained.

27. *Method for a Pipeless Furnace Test.*—The same indirect method of air measurement with some modifications, has been used for calibrating the anemometers for the pipeless furnace tests. Fig.

\* "Report of Progress in Warm-Air Furnace Research." Univ. of Ill. Eng. Exp. Sta., Bul. 112, 1919.

12 shows the anemometer and carriage used for traversing the warm-air face of the pipeless register. This carriage held the anemometer at a distance of 1-1/8 inches from the surface of the register face, and was revolved about the center point. The anemometer at the same time could be moved along the supporting arm and could be made to cover any point on the register face. In making the traverse, the register face was divided into 3 circles and the anemometer held at 4 points on each circle for a period of 5 seconds at each point, making in all 12 positions, taken over a period of one minute. Only two readings of the dial are necessary, one at the start and the other at the end of the traverse. Both readings were taken with the anemometer running in position over the register face, by using the dial switch lever.

The apparatus for calibrating the anemometers for the pipeless furnace tests is shown in Fig. 11. The furnace itself formed part of this apparatus. Air was delivered to the furnace at a point above the bottom of the inner casing by means of a motor driven pressure blower fan. This fan took the air from the laboratory through a 10-1/32 inch wrought iron pipe on which a Pitot tube and piezometer ring were mounted. The Pitot tube and piezometer ring were 16 feet from the entrance to the pipe. A thermometer was also inserted just back of this point. The velocity head in the pipe was measured by means of a Wahlen gage. The whole system, including the furnace, was made air tight, and occasional tests were made with smoke bombs to prove that the system remained air tight. Therefore, the weight of air which passed the Pitot tube was also delivered at the register face.

When it was desired to calibrate the anemometer, the cold-air register face was closed by clamping the plate shown at the left in Fig. 12 over the face. This plate was lined on the under side with felt, which insured an air tight joint. The controlling rheostat on the fan motor, and the furnace dampers were then adjusted until the anemometer gave the same reading as that obtained on the furnace test for which the anemometer was being calibrated, and the air leaving the register face was at the same observed temperature as that obtained on the test. When the preceding conditions had been satisfied, a reading of the velocity head was taken on the Wahlen gage. The anemometer reading could then be compared with the true air velocity through the register grille. This true air velocity was cal-

culated from the weight of air, determined by the use of the Pitot tube, and the temperature at the register face. Under normal conditions, when a test was being run, the calibrating apparatus was closed off from the furnace system by means of a damper, and the furnace took air into the cold-air register face, operating under its own motive head. This method of calibration has proved satisfactory, and has been used for all the pipeless furnace tests included in this report.

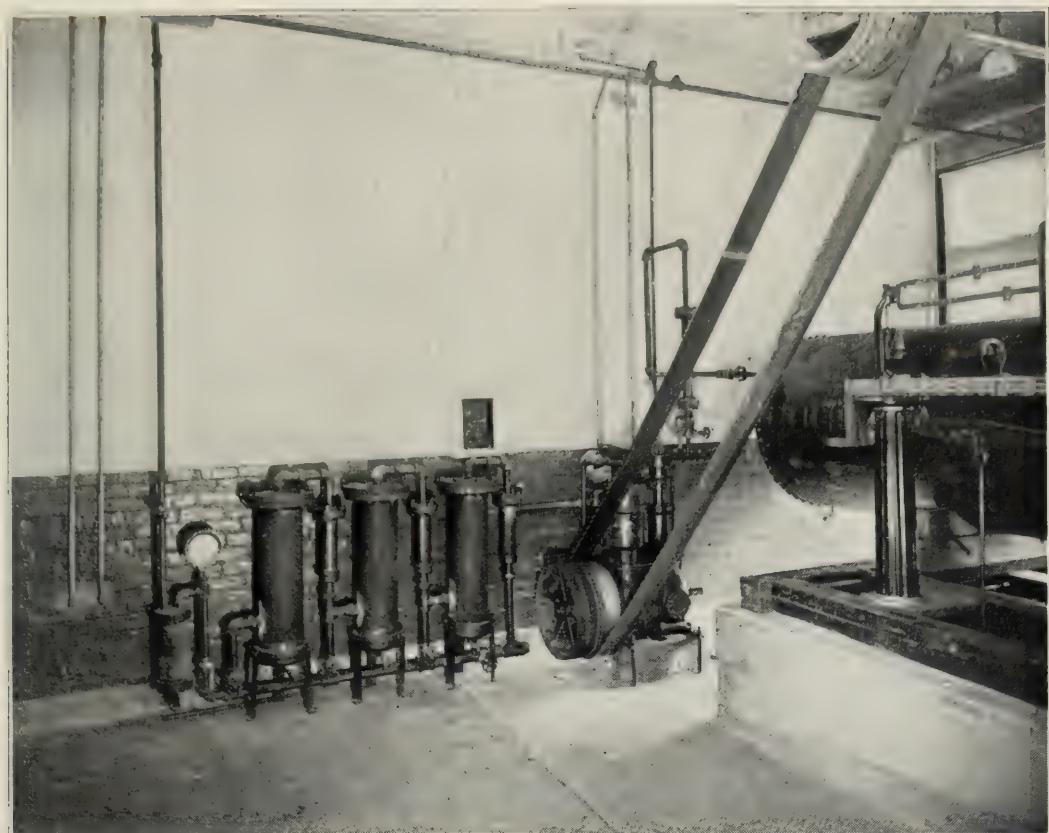


FIG. 28. AIR DRYERS AND COMPRESSOR FOR AIR WEIGHING PLANT

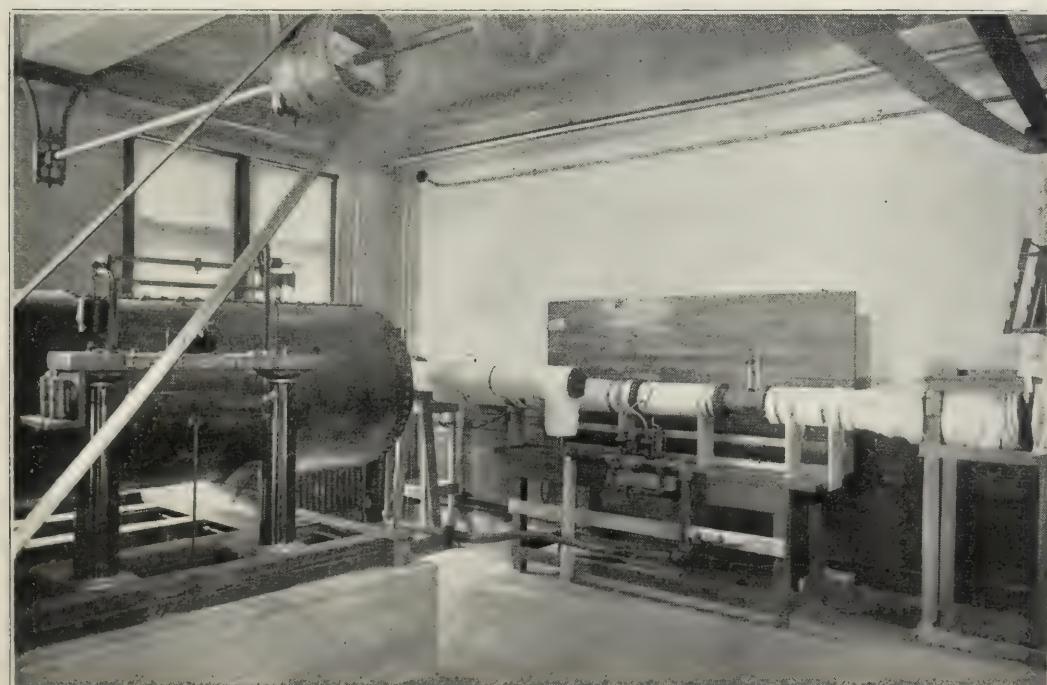


FIG. 29. TANK, SCALES, AND CALIBRATING PIPE FOR AIR WEIGHING PLANT

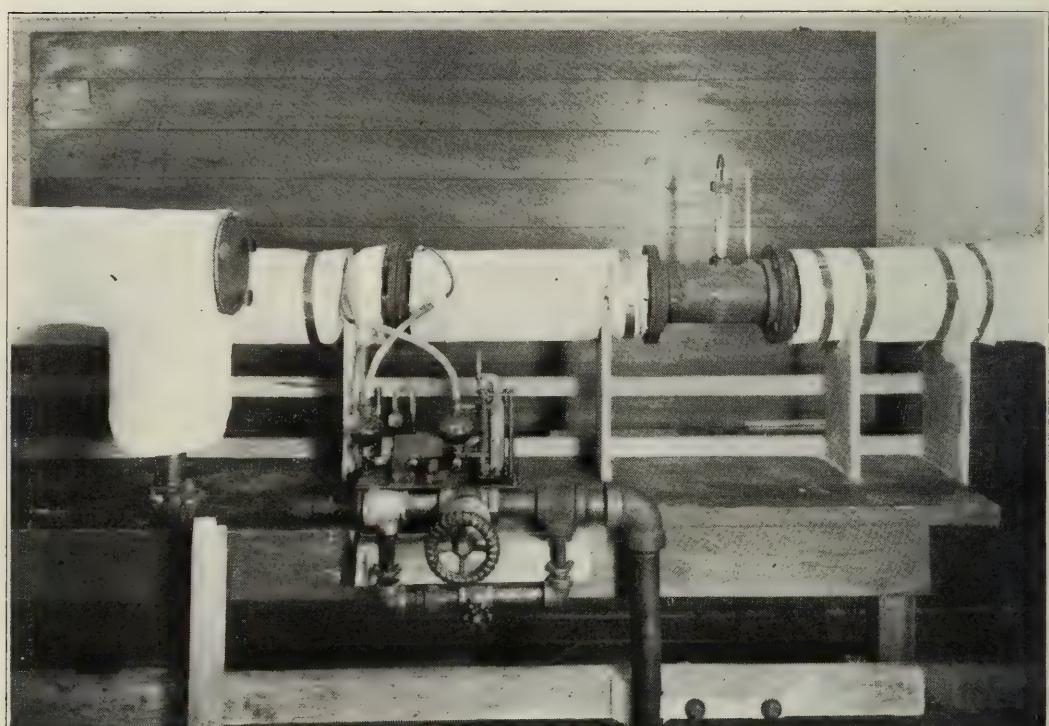


FIG. 30. REGULATING EQUIPMENT FOR CONTROLLING FLOW IN AIR WEIGHING PLANT

## VIII. AIR WEIGHING PLANT FOR CALIBRATION PURPOSES

28. *Description of Plant.*—The plant which has been developed for the calibration of the anemometers used at the register faces of the piped furnace plant is shown in Figs. 28 to 32. The original plant used in some of the preliminary tests consisted merely of a fan having a heater placed in the suction pipe, and a 5 inch delivery pipe in which a Pitot tube was placed. The register heads were attached to the outlet of the 5 inch pipe with suitable connections. This plant is discussed in Section IX.

Certain discrepancies in the results of the piped furnace tests and in the results from anemometer calibrations led to an attempt to check the results by measuring the pressure loss through a calibrated orifice. Wide variations in the weights of air determined by the orifice and the Pitot tube made it evident that some primary method of obtaining the weight of air passing through the system would have to be adopted, and the weighing apparatus in its present form was therefore developed.

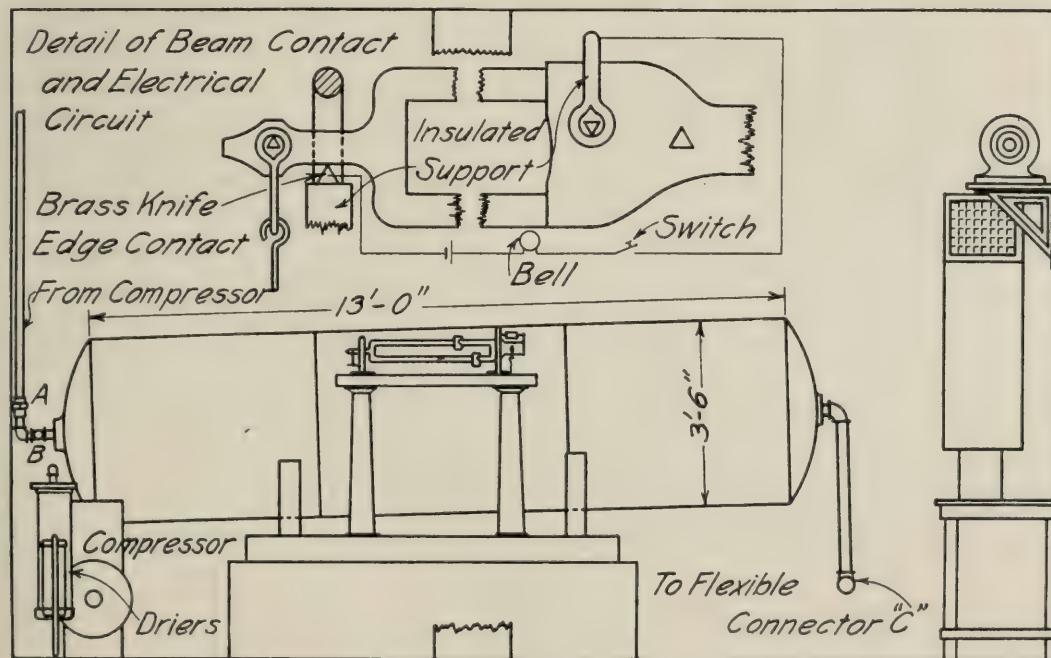


FIG. 31. SECTIONAL ELEVATION OF AIR WEIGHING PLANT

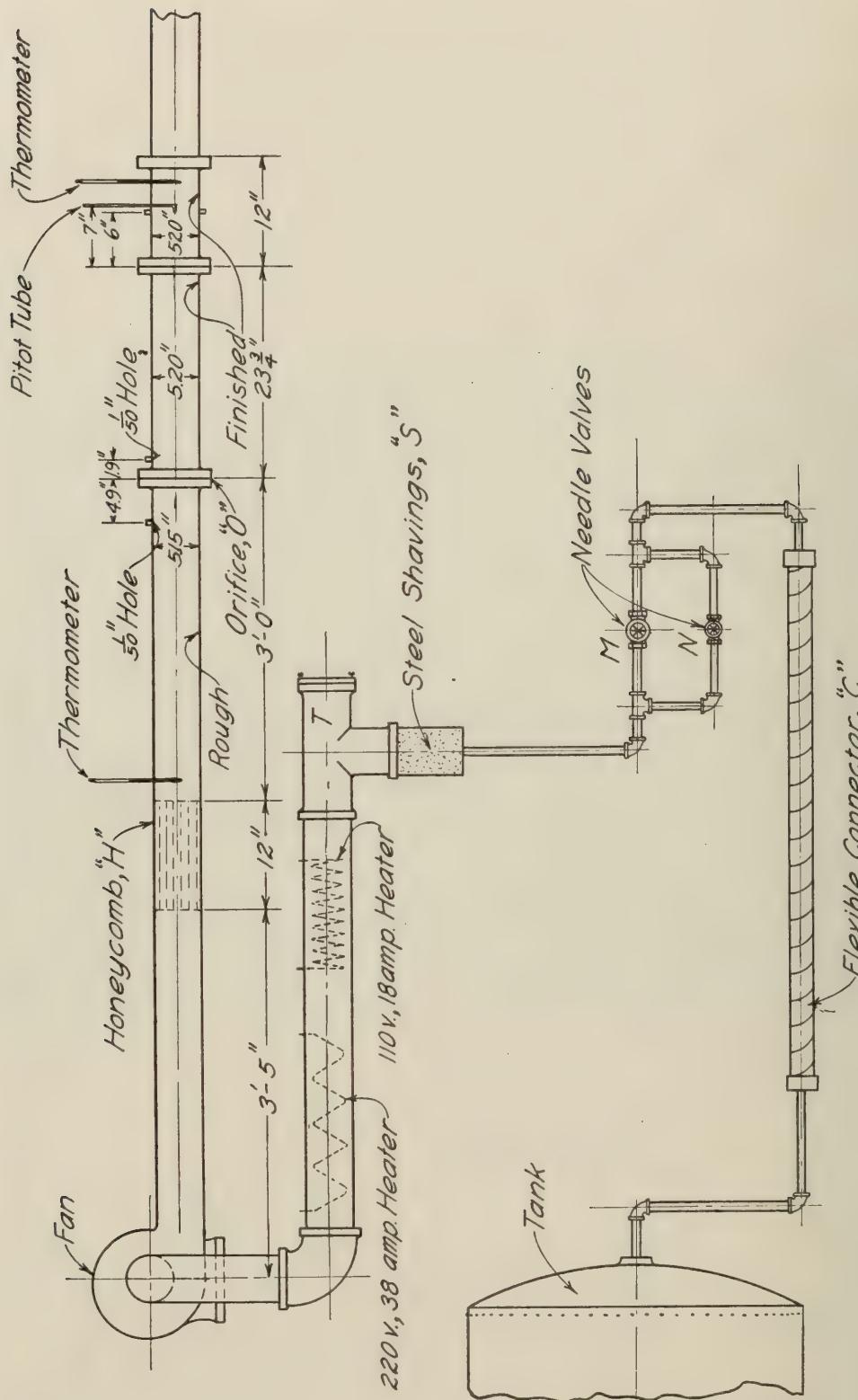


FIG. 32. CONNECTIONS FOR AIR WEIGHING PLANT

Air from the compressed air main in the laboratory is taken into a booster compressor after passing through a separator (Fig. 28) and three calcium chloride dryers. These dryers take out most of the moisture so that a wet and dry bulb psychrometer placed at the register face indicates a relative humidity of approximately 10 per cent at a temperature of 70 deg. F. At higher temperatures the relative humidity, of course, is lower. The air from the compressor is delivered into a tank resting on platform scales. The tank was built for a working pressure of 300 lb. per sq. in. and at this pressure contains approximately 200 pounds of air. Fig. 31 shows the general arrangement of the tank and scale and a detail of the end of the scale beam. The scale used is a Fairbanks No. 2153 four-ton heavy duty built-in suspended-platform scale. The lever ratio is 500 to 1 and the beam is a double beam reading 200 lb. on each beam and graduated to one pound. A brass knife-edge makes contact with the lower edge of the scale beam at about the mid point of its travel. When the beam touches the knife-edge it closes an electric circuit and rings a bell. All weighings are then taken with the beam traveling in the same direction, and at the same point of its travel.

This method of weighing was recommended by Mr. C. A. Briggs of the U. S. Bureau of Standards, who inspected the scale, and who offered many valuable suggestions. The Bureau of Standards has also coöperated with the research staff to the extent of lending four 50 lb. standard test weights to be used for this investigation.

In regard to the accuracy which it is possible to realize, the following paragraph is taken from Mr. Briggs' report on the scale:

"The general principle employed in the weighing appears to promise the highest accuracy which can be obtained from a scale of the character and capacity used. If the scale can remain practically undisturbed throughout the experiments, and vibration can be avoided, it is probable that an accuracy of about 0.01 lb. can be obtained under the best conditions. This may make it possible to reduce the weight of air required and shorten up the time of the experiments. However, the use of the pin point connections where the short levers connect with the long lever, and where the long levers connect with the shelf lever, may reduce the accuracy of the results. This, however, remains to be seen."

In view of the preceding statement, it appears safe to consider that an accuracy within 1 lb. has been attained. Since 150 lb. of

air are always available for a test the error is, therefore, probably less than 0.7 per cent.

A union, *A*, in the pipe line and a valve, *B*, at the tank (Fig. 31) make it possible to disconnect the tank from the compressor when the required pressure is attained, and leave the tank resting freely on the scales. A flexible coupling, *C*, leads from the tank to the valves controlling the flow. With the arrangement of the flexible coupling shown it has been found possible to detect the addition of a weight of 0.2 pound to the scale platform by a change in the position of the scale beam. This was done when the scales were fully loaded. The apparatus is therefore considered sensitive within the limits already stated. Care must be taken not to touch the flexible coupling after a test is started, as it would take a different "set" and thus affect the scale reading.

Fig. 32 shows the general arrangement and dimensions of the apparatus beyond the flexible connector. The flow of the air is controlled by two needle valves, *M* and *N*, one in the main pipe line and one in a by-pass. It has been found possible to regulate the flow within 0.002 inch velocity head at the orifice by means of these valves. After passing the valves the air expands into a chamber of steel shavings, *S*, to break up the effect of stream lines, and thence it passes through two electrical coil heaters. After leaving the heaters, the air goes through a small multi-bladed fan, and enters a straight pipe containing the orifice, *O*, and Pitot tube, *P*. This pipe was built in sections as shown, and the inside surface of each section finished in order that the area of the cross section might be accurately determined, and also that the holes for the piezometer should be flush with the surface. A honeycomb, *H*, with  $1\frac{1}{4}$  inch openings, is inserted in the pipe to straighten the air stream before entering the orifice.

The orifice used in all tests was a thin disk orifice, and the pressure tubes on either side were installed in accordance with the instructions furnished by the maker. The shape of the orifice, and its area, together with the location of the pressure tubes, is shown in Fig. 33. The pressure drop through the orifice is obtained by attaching a Wahlen gage to these pressure tubes. Beyond the orifice is installed the Pitot tube, consisting in this case of the dynamic tube alone. The static pressure connections are located at either side of the pipe. The openings into the pipe for these connections are  $1/50$  inch holes. The temperature of the air is taken by means of a mercury ther-

mometer inserted just after the honeycomb and extending midway into the pipe. All piping from the heaters to the outlet is lagged with magnesia covering to insure as uniform air temperature as possible.

The purpose of the fan, shown in Fig. 32, is to make it possible to calibrate anemometers quickly and conveniently without having to depend upon the air which has been compressed into the tank on the scale. It requires about 3 hours to compress air into this tank to a pressure of 300 pounds per square inch. After the orifice has been calibrated by weighing air passed through it from the tank, a calibration of an anemometer can be made by attaching a register head to the outlet, and comparing the anemometer readings with the rate of air flow as determined by the orifice. This is done by closing the needle valves and loosening the plate at the end of the tee, *T*, which is placed before the heaters. When the fan is started air is drawn through this opening and delivered through the orifice and out through the register head. The amount of air is controlled by using the

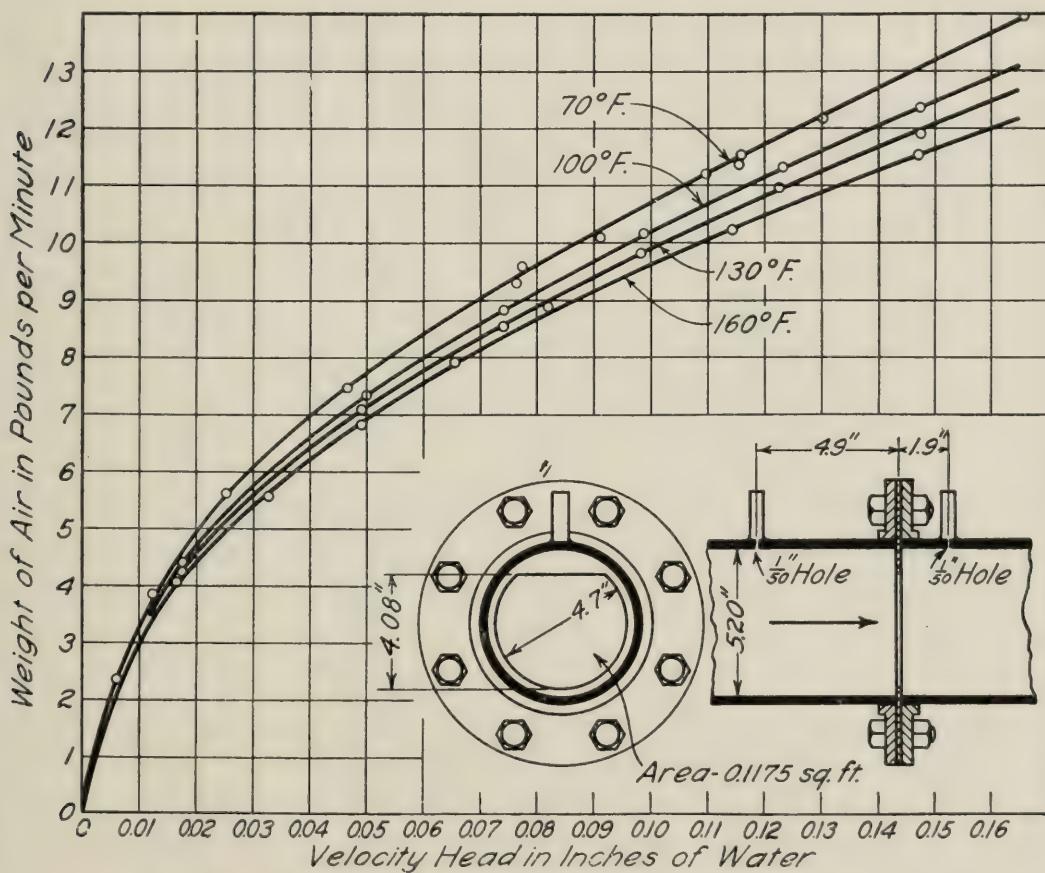


FIG. 33. CALIBRATION CURVES FOR THIN PLATE ORIFICE

plate as a gate valve, thus regulating the size of the opening between it and the pipe. The temperature of the air is controlled by the electric heaters.

Some doubt has been expressed as to whether the conditions at the orifice may not be changed when air is drawn through the heaters and delivered to the orifice by the fan instead of being forced through the heaters and the rest of the system with the fan stationary. Careful tests proved that no difference could be detected in the calibration of the orifice whether the fan was stationary or running. It is therefore considered safe to use the orifice calibration curves for the purpose of calibrating the anemometers when the air is supplied by fan. Greater care has to be taken when calibrating the orifice with the fan running, as small leaks at the stuffing box will materially affect the results. In fact, great care must be exercised at all times to insure that the whole system is air tight. The calibration curves in Fig. 33 were obtained with the fan stationary.

A leakage test was run on the apparatus in order to determine whether any correction should be made for air leakage at pipe threads and in the flexible connector. This was done by pumping the tank up to a pressure of 300 lb. per sq. in., closing the needle valves and valve at the air inlet, and allowing the tank to stand. Periodic observations of the pressure and temperature in the tank were taken. These observations extended over a period of 80 hours. The drop in pressure was then transferred into terms of actual weight of air lost, and the rate of loss in pounds per minute was determined. The results of this test showed an average leakage of 0.01 lb. of air per minute. Since the maximum time of running for any one test was 42 minutes, the maximum correction never exceeded 0.5 lb.

*29. Method of Procedure for Calibration Test.*—The following method of procedure was used for conducting calibration tests on the orifice. The compressor was run until a gage on the tank indicated a pressure of approximately 300 lb. per sq. in. in the tank. The inlet valve was then closed, and the union in the pipe between the compressor and the tank disconnected, thus allowing the tank to rest freely on the scales without interference, except for the flexible connector. A Wahlen gage was attached to the pressure tubes on either side of the orifice, in such a manner that it indicated the pressure drop through the orifice. The plate at the end of the heater

was made tight. The needle valve was then slowly opened until the Wahlen gage indicated the predetermined head for the test. This usually entailed a pressure loss in the tank of about 10 lb. per sq. in. As soon as the flow was under control at the needle valve, the scale beam was balanced so that it rested lightly against the top of the stirrup, and the counterweight was locked. As the air was withdrawn from the tank, the scale beam gradually dropped and, when it touched the knife edge shown in the insert in Fig. 31, it closed a circuit and rang a bell.

This was the signal for the first time reading which was taken by means of a stop watch. After the signal, a 50 lb. standard test weight was placed on the scale platform. This caused the beam to rise to the top of the stirrup. When 50 lb. of air had been taken from the tank the beam again dropped, closing the circuit and ringing the bell, thus giving the signal for the second time observation. Another 50 lb. test weight was then placed on the platform, and in due course

TABLE 5  
RESULTS OF CALIBRATION OF ORIFICE BY WEIGHING AIR

No.	Date	Barometer Inches Mercury	Temperature of Air Degrees F.	Velocity Head Inches Water	Weight of Air Lb. per Min.
1	6-28-20	29.41	81.2	0.0073	2.36
2	6-28-20	29.41	77.5	0.0150	3.87
3	4-16-20	28.79	70.7	0.0307	5.61
4	6-24-20	29.39	71.1	0.0567	7.48
5	4-14-20	28.90	69.9	0.0932	9.30
6	6-24-20	29.43	69.7	0.0944	9.60
7	8-4-20	29.25	66.4	0.1108	10.08
8	6-26-20	29.12	68.8	0.1338	11.21
9	7-16-20	29.29	69.5	0.1410	11.38
10	7-15-20	29.21	68.1	0.1413	11.53
11	6-25-20	29.49	68.8	0.1590	12.19
12	6-25-20	29.49	65.6	0.2022	13.96
13	8-19-20	29.30	100.1	0.0212	4.40
14	8-18-20	29.21	100.0	0.0608	7.34
15	8-20-20	29.27	100.0	0.0905	8.84
16	8-18-20	29.21	100.2	0.1205	10.17
17	8-19-20	29.30	99.9	0.1505	11.32
18	8-17-20	29.34	100.2	0.1800	12.36
19	8-17-20	29.34	129.9	0.0210	4.24
20	8-13-20	29.05	129.9	0.0600	7.09
21	8-21-20	29.11	130.0	0.0903	8.55
22	8-13-20	29.05	130.5	0.1200	9.82
23	8-16-20	29.27	130.2	0.1500	10.98
24	8-16-20	29.27	129.4	0.1800	11.90
25	8-12-20	29.11	160.4	0.0200	4.05
26	8-12-20	29.11	160.0	0.0400	5.59
27	8-9-20	29.18	160.5	0.0600	6.84
28	8-9-20	29.18	161.3	0.0800	7.92
29	7-20-20	29.33	159.0	0.1000	8.90
30	8-11-20	29.21	160.5	0.1400	10.23
31	8-10-20	29.17	160.7	0.1800	11.54

a third time observation made. Since 150 lb. of air was always available, it was always possible to divide a test into 3 parts, and if a uniform rate of flow was maintained it was possible to check the times for the three periods very closely. In most cases, it was found possible to maintain a constant head at the orifice within 0.002 inch of alcohol, and the time intervals checked within one or two seconds.

30. *Results of Calibration of Orifice.*—The orifice has been calibrated over a range of temperatures from 70 deg. F. to 160 deg. F., and for rates of flow varying from 2.36 lb. of air per minute to 13.96 lb. per minute. These results were obtained by Mr. C. Z. Rosecrans, Graduate Research Assistant, working under direction of the research staff, and are shown in the curves of Fig. 33 and in Table 5. Inspection of the curves shows that with very few exceptions the points fall exactly on the curves. This indicates that the apparatus performed consistently and accurately, and demonstrates that weighing air in large amounts for experimental purposes is both feasible and reliable.

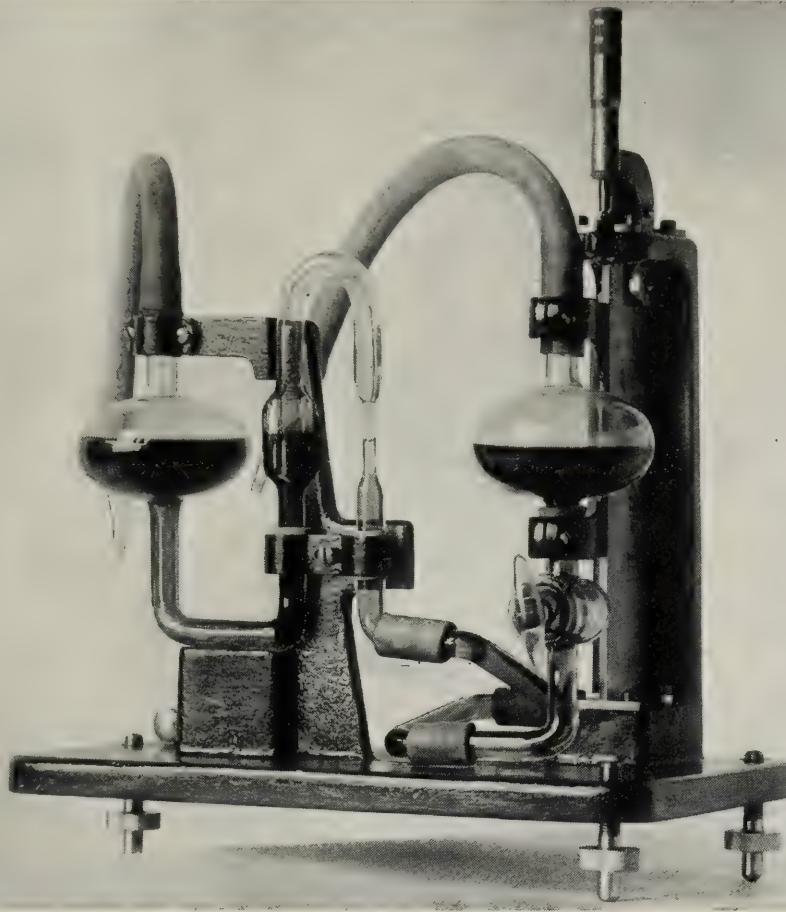


FIG. 34. THE WAHLEN GAGE  
(ILLINOIS DIFFERENTIAL MICROMANOMETER)



## IX. THE WAHLEN GAGE

(ILLINOIS MICROMANOMETER)

31. *Need for a Sensitive Device for Measuring Air Pressure.*—Reference was made in Section VII to the fact that this investigation involved the measurement of unusually low air velocities ranging from 2 to 7 feet per second, or velocity heads of about 0.0015 to 0.0120 inches of water, while the quantities of air flowing were relatively large, ranging from 40 000 to 90 000 cu. ft. per hour. Moreover, the total head for producing flow was extremely slight, amounting to only a few hundredths of an inch of water pressure. In all cases the air was at or very near atmospheric pressure.

It was, therefore, necessary to find some measuring device which would offer no frictional resistance to air flow, would be extremely sensitive, readily portable, simple to operate, and accurate. No such device could be found, although it was believed that if such a gage were used in connection with a Pitot tube, the requirements would practically be met, and it would be possible to measure these low velocities directly. The gage which most nearly met the requirements of the case was the Chattock\* Gage, and one of these gages was constructed, and tested. There was no doubt about its sensitiveness, but certain operating difficulties made its application to the work very troublesome, involving a great deal of labor.

Every possible refinement of measurement was resorted to without complete success until F. G. Wahlen (detailed to this work from the Experiment Station Staff) finally developed a remarkable gage (Fig. 34) so sensitive and accurate that it would measure a pressure head of less than 0.0001 of an inch of water, and respond instantly to the slightest fluctuation in pressure. This equipment is a distinct addition to such precision instruments as are available for measuring low-pressure heads.

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\* See "Report on Wind Tunnel Experiments in Aerodynamics," by J. C. Hunsaker, and others. Page 12, et seq., published by the Smithsonian Institution, Washington, D. C. Jan. 15, 1916

32. *Description of the Gage.*—The essential features of the gage are clearly shown in the illustrations (Figs. 34 and 35), from which it will be seen that a rigid base set on three leveling screws is used to support two large glass bulbs, *A* and *B*, which are in communication with each other through an inverted U tube of peculiar shape. For maximum sensitiveness, it is important that in addition to the constriction in the right hand leg of this tube, there should be an enlargement of the bore in the left hand leg at the plane where the liquids meet. The left hand bulb, *B*, is rigidly attached to the base frame, but the right hand bulb, *A*, moves vertically up or down with the carriage to which it is attached. The motion of this carriage is controlled by practically frictionless guides which eliminate all

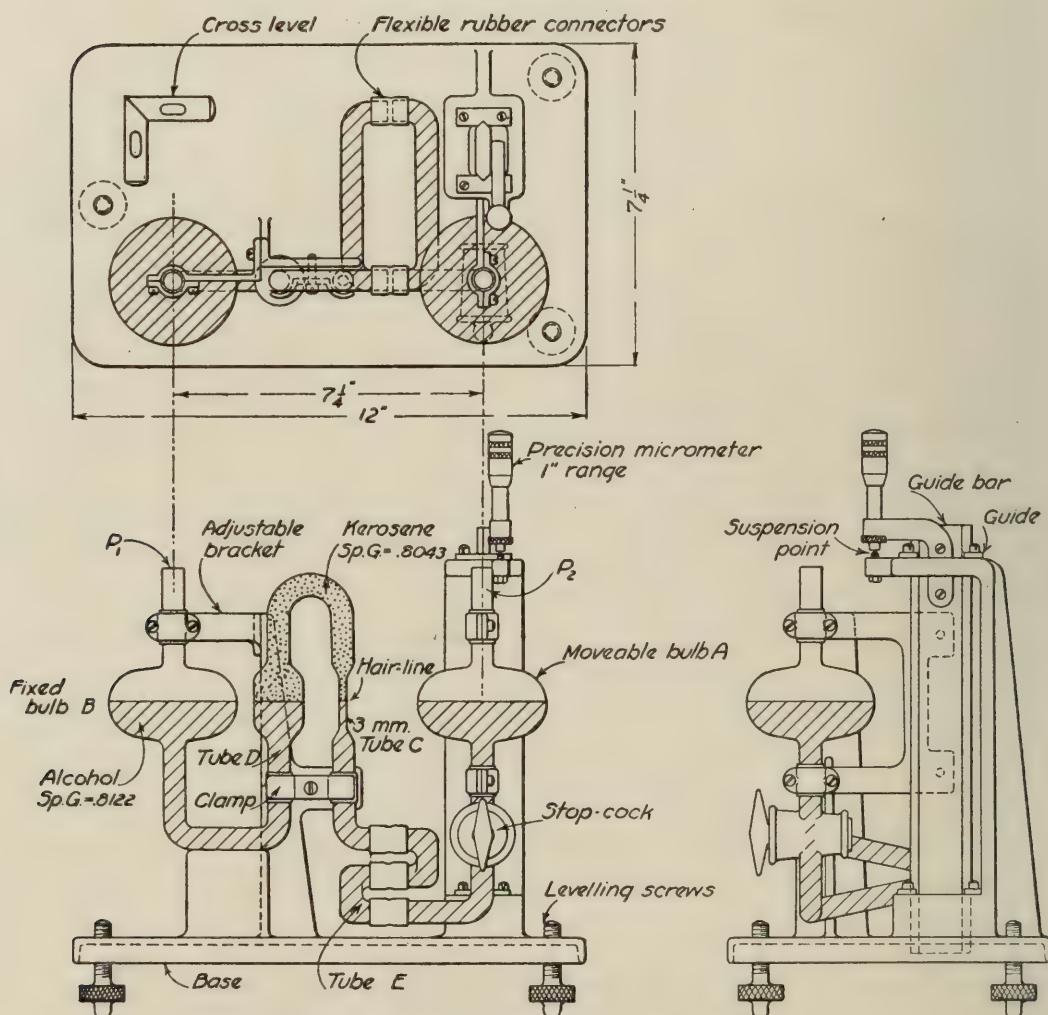


FIG. 35. PLAN AND ELEVATIONS OF WAHLEN GAGE

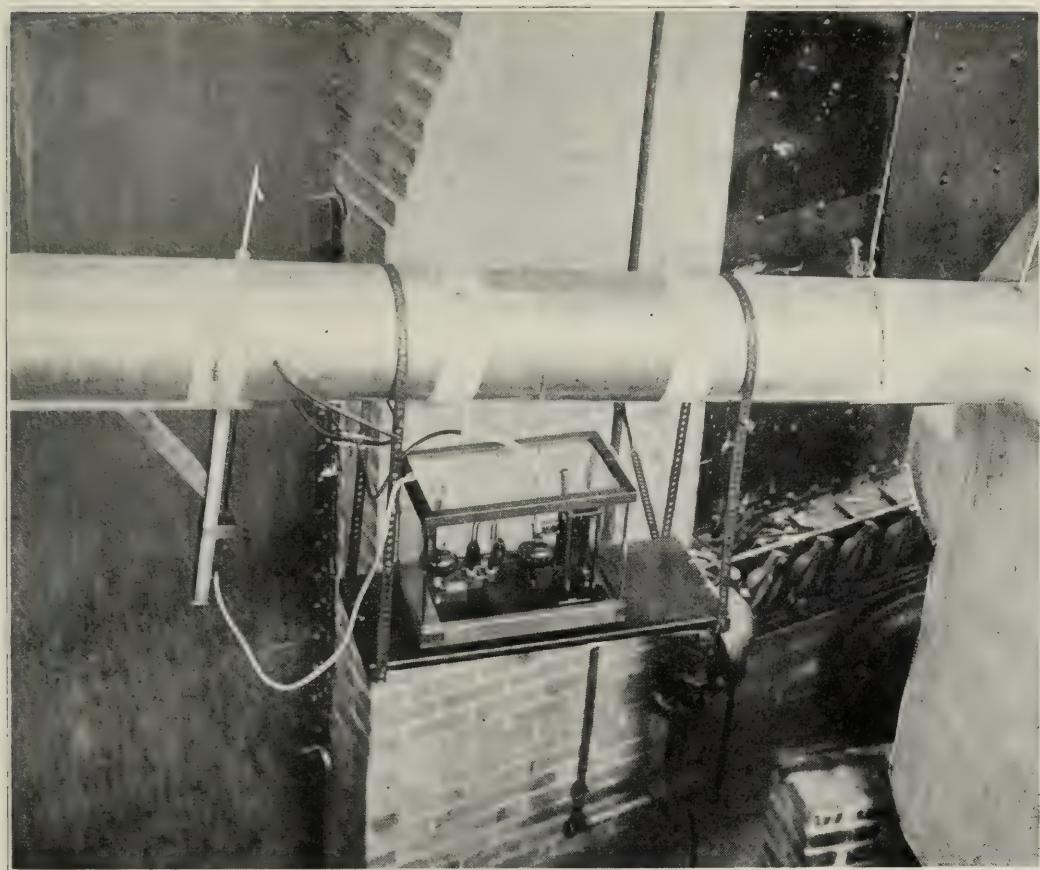


FIG. 36. WAHLEN GAGE IN USE ON A LEADER



back lash or side sway. This movement is under the positive control of a micrometer screw, reading to 0.001 inch direct, and takes place with a slight swivelling action of the joints in the right hand connector tube, *E*. Pressures are communicated to the two bulbs at  $P_1$  and  $P_2$  through the flexible connectors on the top of each.

Alcohol (0.8195) about half fills the bulbs and the U tube, and a little aniline dye gives a distinctive red color. The upper part of the U tube is completely filled with a clear kerosene and ligroin mixture so made up that its specific gravity is 0.0095 less than the density of the colored alcohol.

The specific gravity of the alcohol, which should be saturated with kerosene and ligroin mixture, may vary from 0.8100 to 0.8300 provided the kerosene and ligroin mixture is made up to a specific gravity about 0.0075 to 0.0095 less than the alcohol. In fact, ordinary kerosene (0.8043) may be used as the lighter liquid with complete success if the proper density difference is maintained as stated.

In operation (Figs. 30 and 35), the gage is first balanced at zero with both pressure connections open. It is, of course, necessary to keep the gage always level, for which purpose the three leveling screws and the cross test-level are provided. This balancing is easily done by bringing the meniscus in the constricted side of the U tube (3mm. tube *C*) to a reference hair-line engraved near the center of the tube and then reading the micrometer. This zero setting can be accomplished (without using a microscope) to within 0.0001 of an inch of alcohol, equivalent to about 0.00008 of an inch of water. Pressure connections are then made at  $P_1$  and  $P_2$  and the movable carriage and its liquid bulb, *A*, so manipulated that the meniscus is brought back to the reference line on the U tube, *C*, and micrometer read again. In fact, by proper use of the stop cock in the connecting arm of the gage this meniscus is never allowed to move out of the constricted tube at all. The difference between the two micrometer readings when multiplied by the density of the alcohol gives the pressure head in inches of water. A final zero reading is always taken and must check with the original zero. As the density of the alcohol varies with its temperature a density-temperature calibration curve is used, and the gage may be enclosed in a glass case where there are drafts, as shown in Fig. 36. The curve is plotted from densities obtained at various temperatures to within 0.1 per cent with a Westphal specific gravity balance.

The micrometer screw has a free movement of  $\frac{3}{4}$  inch, hence a pressure difference as great as  $\frac{3}{4}$  inch head of alcohol may be measured.

33. *Method of Filling the Gage.*—The glass ware and rubber tubing must be chemically clean before filling, and the rubber nipples must be unaffected by alcohol.

The liquids are put into the gage as follows: the red alcohol is put in first so that it fills the inverted U tube *C* entirely, all the connections and about one third the bulbs (Fig. 35; a small glass tube with a small rubber tube about four or five inches long is put down the left hand bulb so that the rubber tubing curls around the bottom stem of the bulb, and around the left hand bottom bend of the inverted U tube; a small glass funnel is connected to the glass tube and the kerosene mixture is slowly poured in; it runs down the glass tube through the rubber tubing (controlled by pinch cock) into the inverted U tube where it displaces the alcohol which flows into the bulbs; at the proper time the stop cock is opened a little to flow the mixture evenly into both legs of the U tube to the level of the cross hair on the constricted tube; when the right amount has been added, the glass and rubber tubing is withdrawn and alcohol is added to the two bulbs to make them about half full, and bring the four alcohol levels to the elevation of the cross hair in the constricted tube.

A thousandth of an inch movement of the micrometer screw moves the meniscus about a sixteenth of an inch. The movement of the meniscus may be adjusted to be greater or less, by adjusting the difference of the specific gravities to be greater or less than 0.0085, which was found to be about the "happy medium" for ordinary work.

It will be evident from the preceding statement that, as there has been no movement of the measuring liquid, no corrections are necessary for capillarity, viscosity, variations in bore of tubes, or conditions of glass surface. The sensitiveness of the gage depends, first, upon the relation between the areas of the constricted tube and the large cross section of the bulbs, secondly, upon the viscosity characteristics of the two liquids and the small density differential, and thirdly, upon the fact that the constricted part of the U tube is very short. All other connections are large and free. A standard machinist's precision micrometer forms the measuring element of the

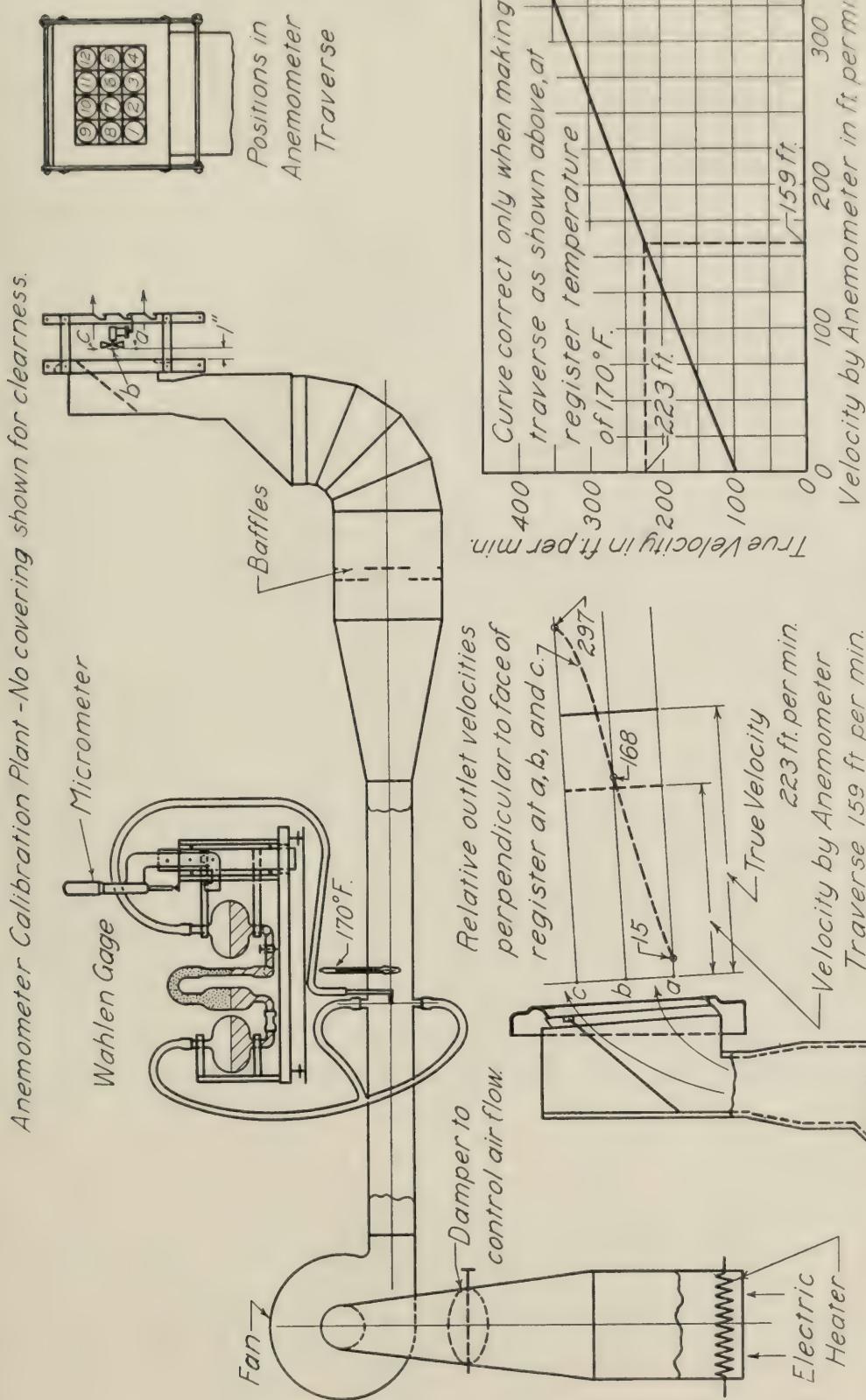


FIG. 37. SECTIONAL VIEW OF PLANT FOR CALIBRATING REGISTER OUTLET ANEMOMETERS, SHOWING USE OF WAHLEN GAGE

gage ensuring a high degree of accuracy within the range of measurement.

34. *Use of the Gage with Pitot Tube.*—The gage may be used as a direct reading instrument in connection with a Pitot tube for measuring and studying the velocity of outflow of air at the end of a pipe or at a register face. In this case, only one pressure tube connection is necessary and the measured head is the velocity head. It is also possible to use the gage for measuring velocity heads or pressures within a pipe, so long as the maximum velocity head or pressure at the section does not exceed the limit of the gage, which is about  $\frac{3}{4}$  inch head of alcohol.

A typical series of measurements of this latter sort is shown in Fig. 27 in which the flow of air in a 10-inch diameter pipe has been measured. In order to do this, the area of the pipe was divided into 5 equal concentric rings and the velocity head measured at the mid-diameter, on two diameters, of each ring. The readings on the vertical diameter only are shown for a mean velocity of about 16 feet per second. It will be noticed that there is a marked variation in velocity across the section and that the maximum velocity is *not* at the center of the pipe by any means. The arrangement of the apparatus is shown in the upper left hand corner of Fig. 37, and it will be evident that the connections are so made at the reading station that the Wahlen gage records only the velocity pressure. The total pressure in the pipe is read by the Pitot tube, but as this includes the static pressure at the section, a second connection is made to the sides of the pipe and the static pressure is admitted to the other bulb of the gage. In this way, the gage is made to indicate only the velocity pressure at the point of the Pitot tube.

The computations for the true mean velocity in the pipe are readily made by use of the hydraulic formula for flow of fluids as follows:

$$V = \sqrt{2gH}$$

$V$  = velocity in feet per second.

$g$  = 32.16 ft. per second per second, acceleration of a freely falling body under attraction of gravity alone.

$H$  = head in feet of air at density of air flowing in pipe.

Since the head is being measured in inches of alcohol and not in feet

of air, certain additional factors must be introduced to transform the head in inches of alcohol into feet of air.

$$Hd = \frac{hak}{12}$$

$d$  = weight of cu. ft. of air at temperature and pressure in pipe.

$h$  = inches of alcohol.

$a$  = specific gravity of alcohol (water 1.0 at 60 deg. F.) at temperature of gage.

$k$  = weight of cu. ft. of water at temperature of 60 deg. F.

12 = inches in one foot.

The practical equation of actual use then becomes:

$$V = \sqrt{\frac{2ghak}{12d}}$$

Moreover, as usually only the mean velocity  $V_m$  is desired, it is necessary to average the sum of all the velocity readings to get  $V_m$ . This is done, for say  $n$  readings, along any one diameter (Fig 27) as follows:

$$V_m = \frac{V_1 + V_2 + V_3 + \dots \text{ to } V_n}{n}$$

or

$$V_m = \sqrt{\frac{2gak}{12d}} \times \frac{(\sqrt{h_1} + \sqrt{h_2} + \sqrt{h_3} + \dots \text{ to } \sqrt{h_n})}{n}$$

in which,

$V_m$  = mean velocity in ft. per. second.

$h_1, h_2, h_3$ , etc. = the heads in inches of alcohol as read.

$n$  = number of readings taken in the traverse.

It will often be found convenient to establish a relation between the velocity at the center of the pipe and the mean velocity. This relation is easily expressed:

$$C = \frac{V_m}{V_c} = \sqrt{\frac{h_m}{h_c}}$$

$C$  = ratio of mean velocity to center velocity,

$V_m$  = mean velocity in feet per second as already stated,

$V_c$  = velocity at center of pipe in feet per second,

$h_m$  = mean velocity head, determined from  $h_1, h_2, h_3$ , etc.,

$h_c$  = velocity head at center of pipe,

and ranges from 0.90 or less to almost 1.0, but varies with size of pipe and velocity of flow.

These measurements are usually made to determine the weight of air flowing per hour, and it is possible to express the result directly as follows:

$$W_{hr} = CV_c Ad \times 3600.$$

$$= C \sqrt{\frac{2gh_cak}{12d}} Ad \times 3600.$$

$$= C \sqrt{h_c ad} \left[ \sqrt{k} \sqrt{\frac{2g}{12}} A \times 3600 \right].$$

The factors in the bracket can readily be expressed as a constant for any given test since  $k = 62.40$ ,  $g$  = the acceleration due to gravity, and  $A$  = the area of the pipe in sq. ft., do not change for a given position on the earth or for a given diameter of pipe. The other values must be obtained for each velocity measurement and have already been described in the preceding. The value of  $d$ , or density of air, is found for dry air as follows:

$$d = \frac{P}{53.35T}$$

$d$  = weight of 1 cu. ft. of dry air.

$P$  = pressure in pounds per sq. ft.

(barometer reading in inches  $\times 0.491$  = pounds per sq. in.)

$T$  = absolute temperature of air flowing, or Fahrenheit temperature + 460.

53.35 = a constant for dry air.

35. *Use of the Gage with Orifice Plate.*—The gage may also be used with a calibrated orifice placed in a pipe line (Figs. 30 and 38) to measure the pressure drop or loss due to the orifice, from which the amount of air flowing through the orifice at the given temperature and pressure in the pipe may be readily determined by reference to calibration curves. Such curves (Fig. 33) are given for a 5-inch diameter pipe, and an orifice plate of the dimensions shown. This method of measuring air flow is quite commonly used, but it is most important that each orifice should first be calibrated for each pipe

diameter by means of a separate testing plant equipped with reliable apparatus. For a method of doing this calibrating work for air at atmospheric pressure and for a rate of flow not exceeding 100 pounds per minute see Section VIII. Not only must the original calibration work be accurately carried out, but the pressure tubes must be inserted before and after the orifice in exactly the same manner and at the same distances as in the original calibration test. (See dimensions in Fig. 38.)

36. *Use of the Gage in Calibrating Anemometer.*—It is not always convenient to use a Pitot tube and Wahlen gage in pipe lines carrying air, and sometimes the measurement can only be made at a register face. Moreover, the velocity at the register face is often very low, especially over certain parts of the face. This means that a very sensitive "field" instrument must be used as an indicator, and

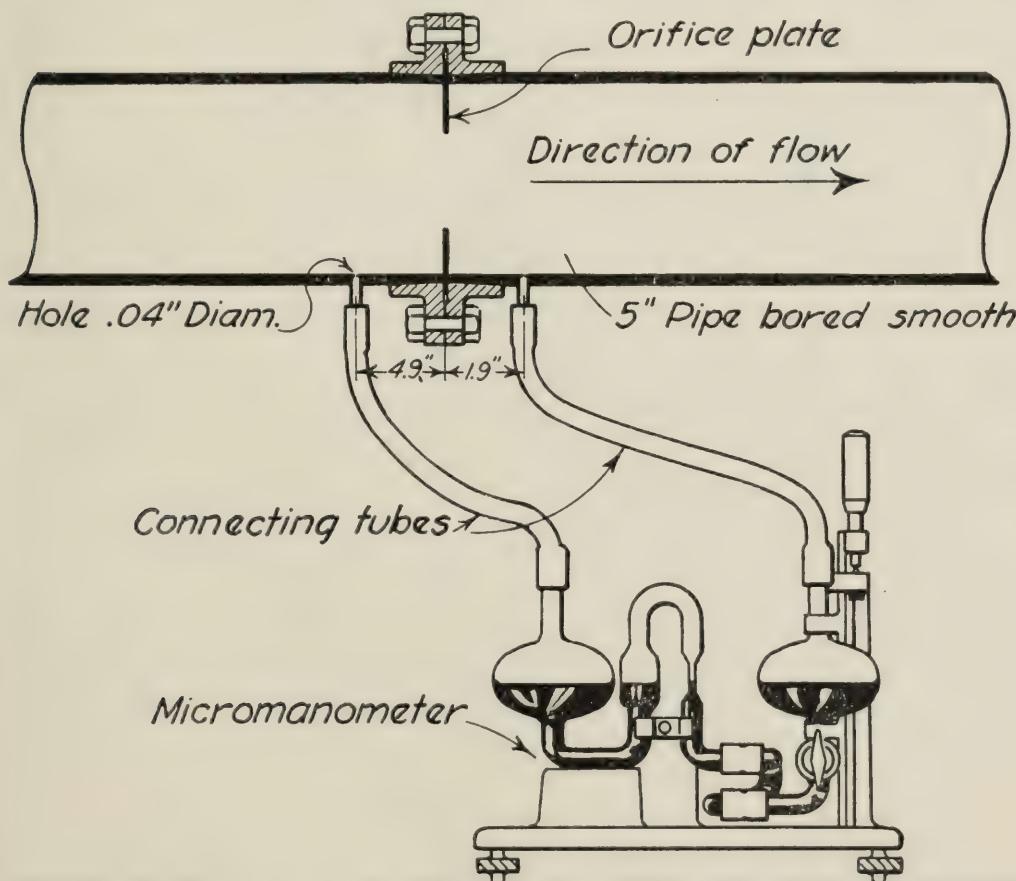


FIG. 38. SECTION OF PIPE WITH ORIFICE AND WAHLEN GAGE IN USE FOR MEASURING AIR

its readings translated into true "outlet" velocities. The grille work in a register is a disturbing factor, as it not only obstructs the area, but causes the air to "speed up" or increase its velocity as it passes through the open spaces between the grilles. The sum of these open spaces is known as the "free area" of the register, and it varies widely with different types. Hence, an instrument used in the plane of the grilles will show a higher velocity than one used either inside or outside of the grilles. Finally, any instrument will be affected by the temperature of the air passing the register face.

As the result of much experimental work, it has been shown that a small (2½ inch fan wheel) anemometer, fitted with jewel bearings, will duplicate its reading when made to traverse a plane one inch in front of and parallel to a register face, for any number of readings, well within 1 per cent, provided the quantity and temperature of the air are kept constant. This field reading is of no absolute value as it is affected by many factors, but if the anemometer can be calibrated in advance *under the identical conditions as regards air temperature, rate of flow, shape of inlet or outlet, and kind and size of registers that exist in the plant under test*, it is a simple matter to measure the air delivery through a register.

This calibrating work has been done in a special plant, (Fig. 37), always available in the furnace research work, in which heated air can be delivered at any desired temperature and velocity through a pipe of known area. This air is then discharged through a register face of the kind to be tested, with the anemometer in question used as the outlet measuring instrument. In its passage through the pipe, the air was accurately measured by Pitot tube or orifice with a Wahlen gage for reading pressures.

Since the air must be heated, an electric resistance heater is placed at the inlet to the suction of a small fan and adjusted to give an outlet temperature corresponding to the actual conditions to be investigated. The fan discharges the air through a 5-inch diameter pipe, where it is measured by the Pitot tube or orifice with great ease and accuracy, as the velocity in the pipe is relatively high compared with the velocity through the free area of the register face.

After the air passes the Pitot tube, it enters an enlarged and well baffled section connecting directly to a standard elbow which turns up into a register box fitted with a sidewall register, as shown

in Fig. 37. This register box and boot are, of course, duplicates of the fittings used in the equipment of the plant under test.

It will be apparent that if the exact amount of air passing the Pitot tube is known, it is a simple matter to calculate the true volume and velocity of air leaving the register face. With the true velocity known it is now possible to calibrate the low velocity instruments, which are anemometers of the best obtainable type. Suitable cross-head guides are attached to the register frame and so arranged that the anemometer attached to the cross-head rod is forced to travel in a uniform and definite manner across the outlet air current at a fixed distance from the register face. As exactly similar guides and the same procedure are used on all registers in the plant under test this same anemometer is put through exactly the same cycle of operations in running a furnace test.

In making the traverse, an initial reading of the anemometer dial is taken with the instrument in position No. 1 and a stop watch is started. The electric heater maintains the desired temperature, since it is most essential that the anemometer be calibrated at the temperature experienced in the test. At the end of five seconds the instrument is moved to position No. 2, and so on through twelve positions, and the final reading only is then noted. In this way it is possible to average automatically the velocity of the outflowing air which, of course, does not flow out uniformly over the area of the face. If the original reading of the dial was 3820 and the final is 3979, the instrument indicates a velocity of 159 ft. per minute at the register. The anemometer will duplicate this reading within one per cent as often as it is desired to check its performance. By calculation from the reading at the Pitot tube, the true velocity was found to be 223 ft. per minute, and hence for this particular set of conditions the anemometer reads too low by 64 ft. per minute.

It is, of course, evident that it would simplify matters greatly if a series of calibrating tests were run in advance for each anemometer. A series of curves could then be drawn similar to the one shown in Fig. 37 from which true velocities at any register temperature could be found as soon as the velocity indicated by the anemometer on any test was known. It is most important to have the calibrating plant constantly available for checking the performance of any anemometer during any test.

## X. HEAT LOSSES FROM A PIPELESS FURNACE

37. *Discussion of Heat Losses from a Furnace.*—The loss of heat from warm-air furnace systems occurs in part by the radiation of heat from the hot surfaces, as well as by conduction and convection. These phenomena take place between the hot surfaces and colder air as explained in Section XII. Radiant heat becomes useful only when it is intercepted by bodies, which in turn give up heat to the air by conduction and convection. Radiant energy is not transmitted directly to dry air. To obtain the maximum heat energy from the furnace and connected piping, it is necessary not only to intercept the radiant heat, but also to insulate the exterior surfaces, and thus retain the heat so that the air in its passage through the furnace will absorb by conduction and convection the maximum amount of heat, and at the same time give up the minimum amount of heat when passing through the various pipes and fittings.

Heat losses from warm-air furnaces are detrimental to the best efficiency of operation for two reasons, first, because of the actual loss in the heating value of the warm air, and secondly, because of the loss in motive head brought about by the drop in temperature of the air.

This section deals with the various sources of heat loss from a pipeless furnace, and the effect of such heat losses on motive head. The force or head which produces the flow of air in gravity warm-air installations is determined by the difference in weights of the cold-air column on one side of the system and the hot-air column on the other. The greater the difference between the weights of these two columns the greater is the air handling capacity of the furnace.\* Any loss of heat from the hot-air column results in an increased density or weight on the hot side of the system with the result that the motive head is decreased; likewise, any increase in the temperature of the air on the cold side of the system results in a lighter column of air on the cold side and a decreased motive head. The two cases are exemplified

\*See "Fuel Economy in the Operation of Hand Fired Power Plants." Univ. of Ill. Eng. Exp. Sta., Circ. 7, p. 55, 1918.

in practice by the piped furnace and the pipeless furnace. In the piped furnace, the motive head is decreased by radiation of heat from pipes and casing; and in the pipeless furnace the head is decreased by the transmission of heat through the inner casing to the down-coming cold air. Heat losses must therefore be reduced to a minimum if the maximum air handling capacity is to be obtained.

38. *Radiation Losses from a Pipeless Furnace.*—The tests herein reported were made for the purpose of estimating the radiation losses from pipeless furnaces, and determining the probable overall efficiency of the furnaces, after making due allowance for radiation of heat from the discharge register. This radiant heat, although effective in heating, is not measurable with the present equipment, and in previous tests has been included in the item "Heat lost by radiation and unaccounted for." The amount of this radiant heat can be estimated and readily included in the overall furnace efficiency.

The tests used as the basis for this discussion were made on a pipeless or duplex register furnace, the same equipment as was used in pipeless furnace tests 1 to 12 inclusive (Table 1 and Fig. 9). It must be understood, therefore, that the following data are correct only for the equipment used and at the particular temperatures stated. However, they may be applied as an approximation to any pipeless furnace of the same type, over an ordinary range of temperatures.

The determination of the radiation losses from the furnace was made by measuring the temperatures and areas of the various exterior radiating surfaces of the furnace, and calculating the losses, using the emissivity coefficients for the various materials. These coefficients were determined on the special steam drum plant for measuring heat losses from various surfaces.\*

The accompanying sketch (Fig. 39) and calculation of areas indicate the manner in which the radiation losses were assumed to be distributed, and give the various temperatures as measured in test No. 9, December 9, 1920 (Table 1). The losses (Table 6) were assumed to occur through, first, the cast-iron furnace front, secondly, the lower casing exposed to direct radiation from the fire-pot, thirdly, the upper casing indirectly heated, fourthly, the concrete floor, and fifthly, the open register face. Temperatures of the radiating sur-

\* See "Emissivity of Heat from Various Surfaces." Univ. of Ill. Eng. Exp. Sta., Bul. 117, 1920.

TABLE 6  
ESTIMATED RADIATION LOSSES FROM A PIPELESS FURNACE

Location of Surface	Loss B.t.u. per Hour	Loss Expressed as Per Cent of Total Loss
From furnace front.....	5700	48.30
From concrete floor.....	3120	26.50
From lower casing below shield.....	830	7.05
From upper casing.....	2140	18.15
Total loss.....	11 790	100.00

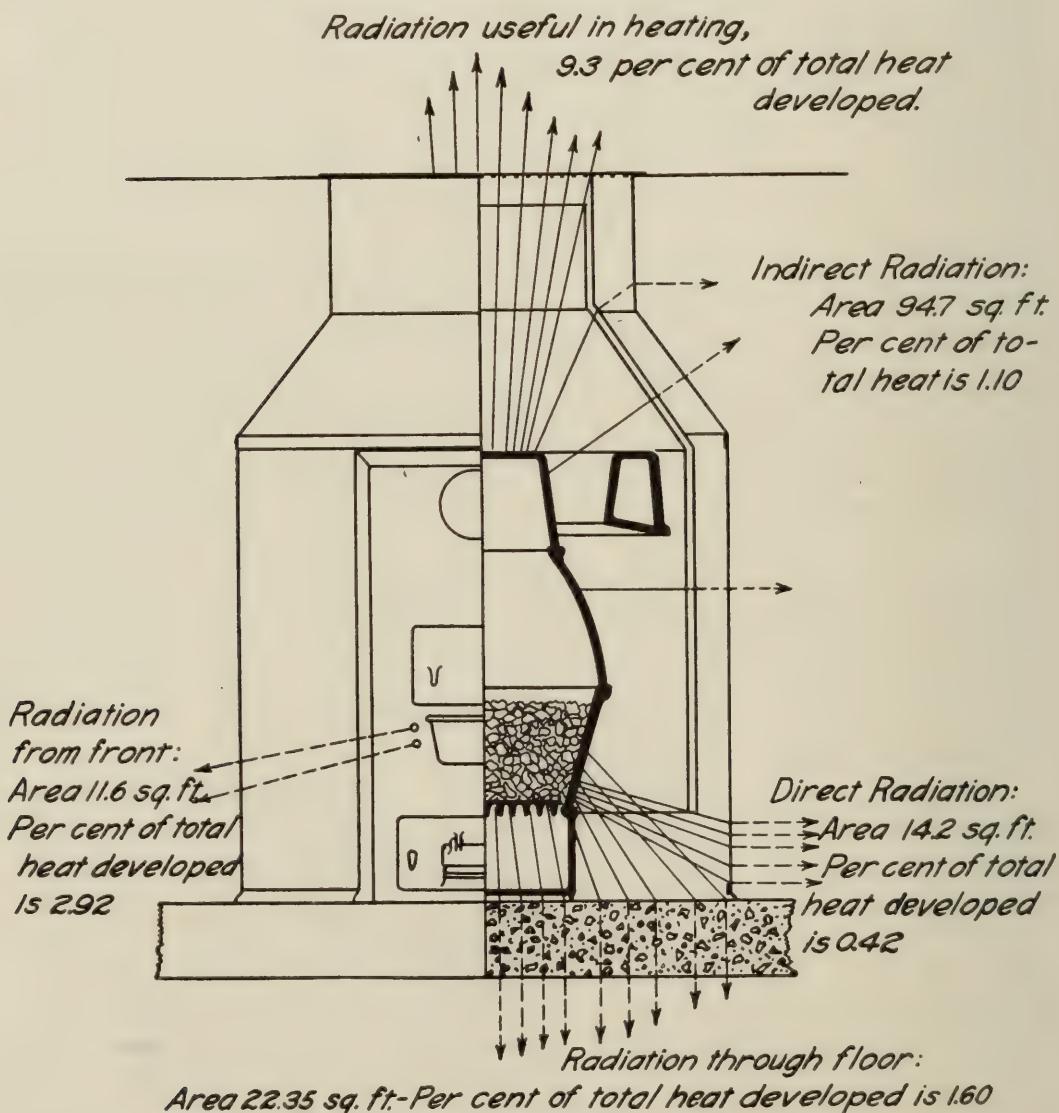


FIG. 39. DISTRIBUTION OF RADIATION LOSSES FROM PIPELESS FURNACE

faces were measured by thermometers attached with putty or plaster of Paris. In the case of the concrete floor, a special problem was involved. Since the floor was 10 inches thick it required several hours to heat. In this case six thermometers were attached to the underside of the floor. Readings of the thermometers were made every half hour during the test (No. 9, pipeless furnace) and the readings averaged and plotted. The accompanying "Heating Curve" (Fig. 40) represents these temperature measurements, and indicates that at 143 deg. F. the temperature of the floor became constant, and that the emission of heat continued thereafter at a constant rate.

No account was taken of the fact that some heat was dissipated by conduction in the 10-inch concrete floor. This heat was carried away in the floor and gradually heated it in a wide circle surrounding the furnace. The actual extent of this unaccounted-for loss was not

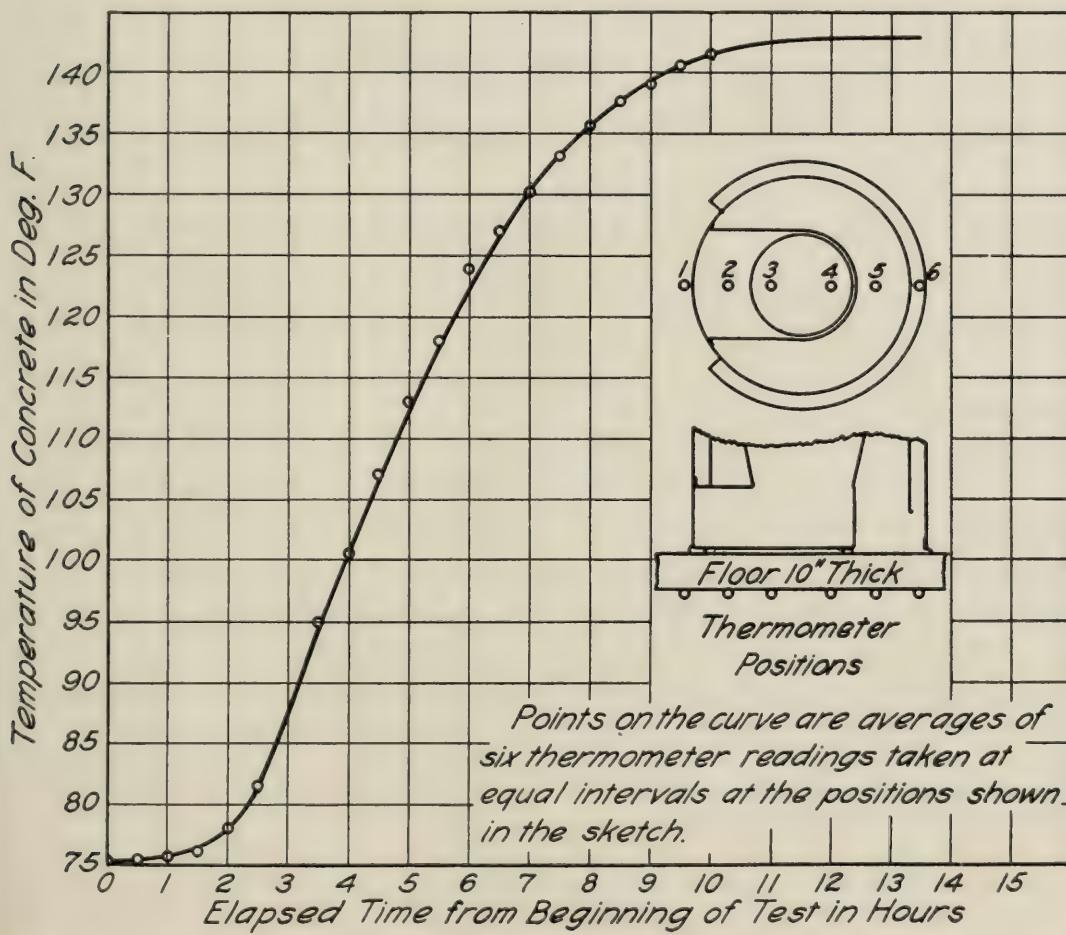


FIG. 40. TEMPERATURE CURVE FOR CONCRETE FLOOR UNDER A PIPELESS FURNACE

considered to be great, as the floor temperatures surrounding the furnace did not increase appreciably.

The determination of emissivity coefficients for the concrete floor and for the blackened cast-iron furnace front necessitated special emissivity tests. For these tests a drum covered with a  $\frac{1}{4}$ -inch coating of concrete was used, and also a black iron drum painted with the same dull black paint as the furnace front. These drums were tested in the same manner as the specimens described in Engineering Experiment Station Bulletin 117, and the results are, therefore, comparable with those of the previous tests. The data for these special tests of the two surfaces may be found in Figs. 43a, b and c, Specimens Nos. 28 and 29. Values of 2.08 and 2.20 B.t.u. per sq. ft. per hour per degree difference in temperature were found for the concrete and the black iron respectively.

Per cent of total heat developed\* lost by radiation

$$= \frac{11790 \times 100}{195100} = 6.04.$$

Heat loss by radiation expressed as per cent of the heat put into air.\*

$$= \frac{11790 \times 100}{127600} = 9.24.$$

Heat lost per pound coal burned, B.t.u.

$$= \frac{11790 \times 10}{152.8} = 772.$$

Item 62 of pipeless furnace test No. 9 (Table 1) gives a "Radiation and unaccounted for loss" of 1966 B.t.u. per pound of coal burned. Of this loss, 772 B.t.u. have been accounted for. The remainder of the loss, 1194 B.t.u. per pound of coal burned, has been ascribed to useful radiation from the register face.

The effect of the radiant heat issuing through the register face upon the heating capacity of the furnace was to increase the useful heat per pound of coal by 1194 B.t.u., or  $8350 + 1194 = 9544$  B.t.u. per pound of coal was useful in heating, and the efficiency then was increased from 65.3 per cent to

$$\frac{9544}{12791} \times 100 = 74.6.$$

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\*See Pipeless Furnace Test No. 6, Table 1.

This is an increase in efficiency of 9.3 percent over the value given in Pipeless Furnace Test No. 9. It represents the approximate amount which may be added to the efficiency, based on the heat carrying capacity of the air, in order to determine the true overall efficiency.

**Heat Loss Calculations used in Table 6.**

Cast iron front with black Pecora paint.

$$K \text{ from test} = 2.20 \text{ B.t.u. per sq. ft. per hr.}$$

$$\text{Loss} = 2.20 \times 11.6 \times (300 - 77) = 5700 \text{ B.t.u. per hr.}$$

Concrete floor exposed to radiation.

$$K \text{ from test} = 2.08 \text{ B.t.u. per sq. ft. per hr.}$$

$$\text{Loss} = 2.08 \times 22.35 \times (143 - 76) = 3120 \text{ B.t.u. per hr.}$$

Casing exposed to radiation from fire-pot direct.

$$K \text{ from Bulletin 117} = 1.33$$

$$\text{Loss} = 1.33 \times 14.2 \times (120 - 76) = 830 \text{ B.t.u. per hr.}$$

Casing not directly exposed to radiation.

$$\text{Loss} = 1.33 \times 94.7 \times \left( \frac{(107 + 79)}{2} - 76 \right)$$

$$= 1.33 \times 94.7 \times (93 - 76) = 2140 \text{ B.t.u. per hr.}$$

## XI. EMISSIVITY OF HEAT FROM VARIOUS SURFACES

39. *Previous Investigations.*—In May, 1919, it was observed in certain tests with a single leader pipe that a greater temperature reduction occurred in air passing through bright tin pipes covered with asbestos paper, such as are commonly used in furnace heating, than in air passing through the same bright tin pipes uncovered, all other conditions in the comparative tests remaining the same. It was therefore evident that the heat loss was greater through the asbestos-paper-covered pipes than through the same pipes uncovered.

Because of the inefficacy of many of the present methods of insulating warm-air furnaces, it was evident that a complete study of various heat insulating materials, coverings, and surfaces would be justified, and such a study has been made and reported in an earlier publication.

40. *Significant Conclusions from Previous Investigations.*—The following significant conclusions appearing in the former bulletin\* are deserving of special emphasis:

(1) The use of thin sheets of asbestos paper on bright tin leader pipes results in a waste of heat. The use of thin sheets should be abandoned.

(2) Uncovered bright tin pipes are more efficient carriers of heated air than asbestos-paper-covered bright tin pipes. See item (4).

(3) This fact is true regardless of the degree of brightness of the tin surface.

(4) No small number of applications of asbestos paper will suffice as an insulator. Several thicknesses are necessary to make a covering equal in this respect to the bare tin.

(5) The accumulation of dust and dirt on the pipes does not greatly alter the amount of the loss.

(6) The heat loss from warm-air furnace pipes covered with one layer of asbestos paper is an important item in the cost

\* "Emissivity of Heat from Various Surfaces." Univ. of Ill. Eng. Exp. Sta., Bul. 117, 1920.

of heating, amounting generally to more than 5 per cent of the coal consumption, depending upon the number and size of the pipes used.

(7) The fact that pipes are partly protected from convection currents of air by joists and studding does not greatly affect the loss.

(8) Unless the insulating covering material excels the uncovered bright tin in heat insulation properties it should not be used.

(9) Such materials are available and the tests have shown their merits.

The apparatus shown in Fig. 42 was that used in the tests reported in Engineering Experiment Station Bulletin No. 117. It consisted of low-pressure-steam-heated drums, five in number, surrounding a central steam header from which the drums drew their supply of steam. The drums were uniform in size, ten inches in diameter by twenty inches in length and were made of sheet metal of the kind to be tested. Steam was condensed in the drums by the

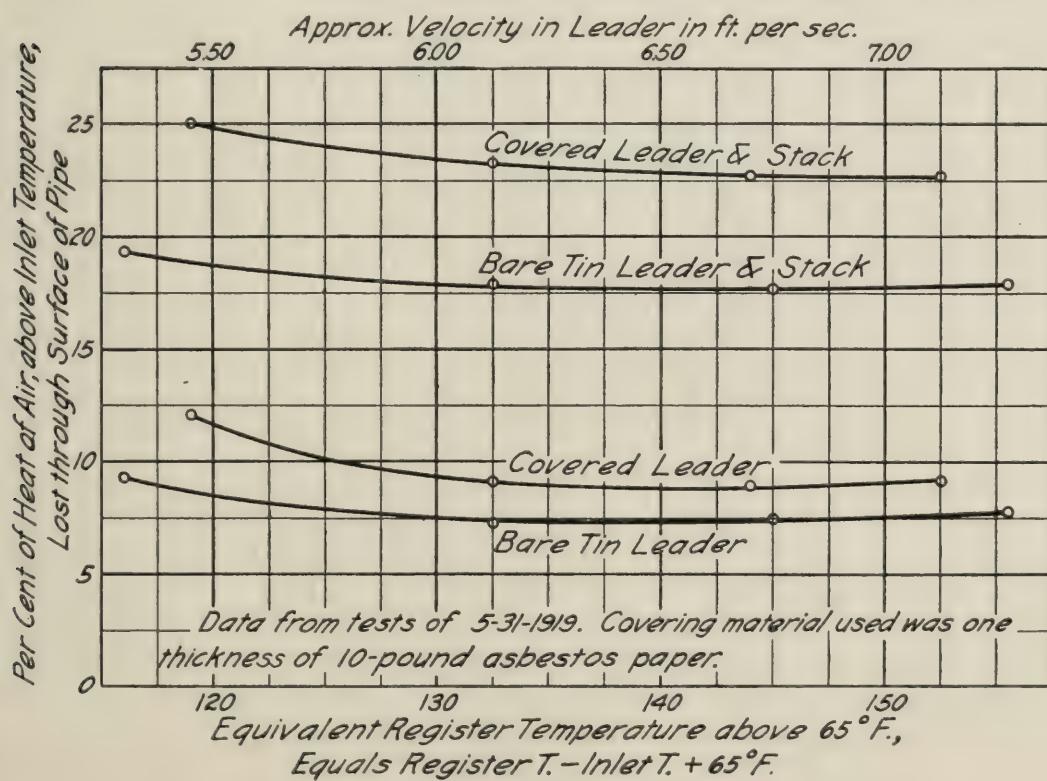


FIG. 41. HEAT LOSSES FROM LEADERS AND STACKS, COVERED AND UNCOVERED

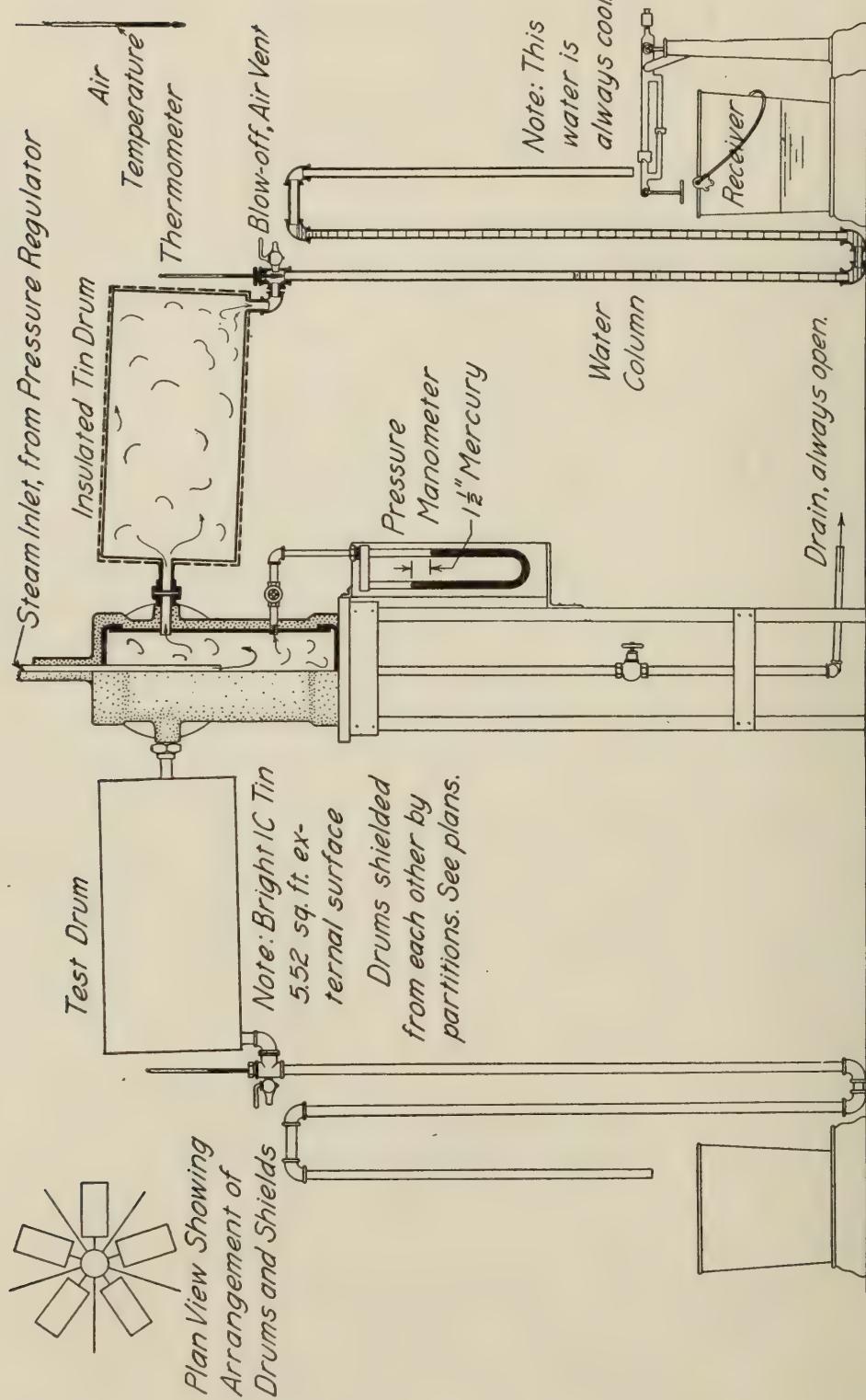


FIG. 42. SECTIONAL ELEVATION OF STEAM DRUM PLANT FOR TESTING SURFACES FOR EMISSIVITY

cooling action of the air surrounding them, and the condensate was discharged through water seals connected to each drum. These seals were U tubes made of pipe, and were long enough to contain a water head of four feet. As the steam condensed, the seals filled with water, and the condensate then dripped over into receivers as fast as it accumulated. The water in the seals cooled to room temperature before it entered the receivers so that practically no evaporation took place from the surface of the water in the receivers. Each receiver was mounted on a small weighing scale accurate to one one-hundredth pound.

The weight of steam condensed by a drum was an indication of the relative merit of the surface as a heat insulator.

41. *Specimens Tested.*—A complete list of the drums tested is given in Figs. 43a, 43b, and 43c. In the list will be found a description of the insulation or the nature of the surface, the actual area of the drum exposed to the steam, and a serial number assigned to the drum which will be useful in connecting the description with the results reported.

42. *Discussion of Results.*—The significance of the results of the tests may be best understood by a study of the information presented in the diagrammatic chart, Figs. 43a, 43b, and 43c. The heavy black bars afford a graphic comparison of the heat-emitting value of the various surfaces. Reference must be made to the descriptive list of drums in order to connect the data with the corresponding test specimens. The relative efficiencies of the various surfaces as heat insulators are given in the next to the last column of the chart. The coefficient of emissivity\* for bright IC tin was used as the basis for this comparison.

The results of these tests present very convincing evidence against the use of thin layers of asbestos paper covering on bright tin pipes. The heat loss was 62 per cent greater with one thickness of the paper covering a bright tin pipe than when the same pipe was left uncovered. The importance of this loss may be seen by the fact that it results in a waste of 5 per cent or more of the coal consumed in the average house furnace.

\* See "Emissivity of Heat from Various Surfaces." Univ. of Ill. Eng. Exp. Sta., Bul. 117, 1920.

Drum Number	Description of Surface	Area Exposed to Steam sq. ft.
1	1C tin, not insulated, bright	5.53
1a	Same as No. 1 with ash dust sifted on $\frac{1}{16}$ " deep	5.53
2	1C tin with 1 thickness of 10-pound asbestos paper	5.52
3	1C tin with 3 thicknesses of air-cell asbestos and 1 thickness of 10-pound asbestos paper	5.50
4	1C tin with 2 applications of gray paint, (of zinc, linseed oil, and lithpone composition)	5.51
5	1C tin with 1 thickness of asbestos paper and 2 applications of paint, (No. 2 drum with same kind of paint as used on No. 4)	5.52
6	1C tin with 1 thickness of air-cell asbestos and 1 thickness of 10 pound asbestos paper, (No. 3 drum used)	5.50
7	1C tin nickel plated and polished	5.54
8	Galvanized iron, No. 28 U.S.S. gage	5.53
9	Black iron, No. 28 U.S.S. gage, very rusty	5.52
10	Surface and drum No 3 with 1X tin casing surrounding, with $\frac{5}{16}$ " air-space and with 6 $\frac{1}{2}$ " vent holes cut in the casing	5.50
11	1C tin (drum No. 1) coated with Bakelite lacquer	5.53
12	Same as No. 10 but with vents stopped	5.50
13	1C tin (drum No. 2) with 1 thickness of 10-pound asbestos paper and a surface of glaze finish printers' proofing paper	5.52
14	1C tin drum No. 4 with paint removed and a housing of compo-board construction, to represent joists, built around same. Housing 8" deep by 14" wide by 28" long	5.51

FIG. 43a. DIAGRAMMATIC TABLE OF ONE HUNDRED

Coefficient of Emissivity - K B.t.u. per sq.ft. per hr. per 1°F.												Relative Efficiency Per Cent	Drum Number
0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0	2.2	2.4	
										1.280	100.0	1	
										1.440	89.0	1a	
										2.080	61.5	2	
										0.565	226.0	3	
										2.225	57.5	4	
										2.155	59.5	5	
										0.870	147.0	6	
										1.330	96.0	7	
										1.330	96.0	8	
										2.370	54.0	9	
										0.700	183.0	10	
										1.575	81.5	11	
										0.593	216.0	12	
										1.800	71.0	13	
										1.430	89.5	14	

AND SEVENTY TESTS ON STEAM DRUMS

Drum Number	Description of Surface	Area Exposed to Steam sq.ft.
14a	Same as No. 14 with housing removed	5.51
15	Same as No. 10 but with the air-space packed with dry JM asbestos cement	5.50
16	1C tin with 2 thicknesses of 12-pound asbestos paper	5.52
16a	Same as No. 16 with ash dust sifted on $\frac{1}{16}$ " deep	5.52
17	1C tin (drum No. 2) with 3 thicknesses of 12-pound asbestos paper	5.52
18	Galvanized iron (drum No. 8) with 3 thicknesses of air-cell asbestos and 1 of 12-pound paper	5.53
19	1C tin (drum No. 2) with 4 thicknesses of 12-pound asbestos paper	5.52
20	1C tin with 1 thickness of asbestos paper covered with a firm coating of white calcimine, (for determining the effect of light and dark surfaces)	5.51
21	Galvanized iron (drum No. 8) with $1\frac{1}{4}$ " Asbesto-cel blocks covered with $\frac{1}{2}$ " of asbestos cement and a cheesecloth wrapper	5.53
22	1C tin (drum No. 2) with 5 thicknesses of 12-pound asbestos paper	5.52
23	Same as drum No. 20 with lampblack calcimine on the surface used in that test	5.51
24	1C tin (drum No. 2) with 6 thicknesses of 12-pound asbestos paper	5.52
25	1C tin (drum No. 2) with 7 thicknesses of 12-pound asbestos paper	5.52
26	1C tin (drum No. 2) with 8 thicknesses of 12-pound asbestos paper	5.52

FIG. 43b. CONTINUATION OF DIAGRAMMATIC TABLE OF

Coefficient of Emissivity-K B.t.u. per sq.ft. per hr. per 1° F.								Relative Efficiency Per Cent	Drum Number
0	0.2	0.4	0.6	0.8	1.0	1.2	1.4		
								1.520	84.3
								0.899	142.0
								1.880	68.1
								1.820	70.5
								1.790	71.5
								0.577	222.0
								1.670	76.5
								2.050	62.5
								0.326	392.0
								1.435	89.0
								2.120	60.5
								1.390	92.0
								1.320	97.0
								1.260	101.5
									26

ONE HUNDRED AND SEVENTY TESTS ON STEAM DRUMS

Drum Number	Description of Surface	Area Exposed to Steam sq.ft.
27	1C tin with 3 ply $\frac{1}{8}$ " Carocel paper	5.53
28	Black iron, No. 28 U.S.S. gage, painted with dull black Pecora paint	5.53
29	1C tin with 2 ply $\frac{1}{4}$ " of smooth concrete	5.53
30	1C tin with 2 ply $\frac{1}{8}$ " Carocel paper	5.53
31	1C tin with single ply Carocel paper	5.53

FIG. 43c. CONTINUATION OF DIAGRAMMATIC TABLE OF

The fact that the heat loss from warm-air pipes of a furnace system is of some magnitude is not generally appreciated. A considerable part of the heat in the air flowing through the pipes of the average installation is dissipated from the pipe surface and received by surrounding air and nearby objects. Fig. 41 shows the results of tests made to determine the amount of this loss. The tests were made on a single leader pipe furnace,\* (Fig. 50) in which the quantity of air handled and the heat added to the air above the entering temperature could be readily ascertained. The heat loss was calculated from the drop in temperature of the air in its passage through the pipe. The temperatures and velocities indicated by the curves are representative values.

In order to demonstrate the inefficiency of thin layers of asbestos paper as a heat insulator, tests were run in which the number of thicknesses of paper was increased until the heat loss became less than the loss through a bare bright tin specimen. The curve (Fig. 44) gives the results of these tests. Eight thicknesses of twelve-pound asbestos paper were applied before the desired result was obtained. In these tests the moistened paper was wrapped tightly around and shrunk on the drums so that only a small quantity of air was entrapped between the successive layers of paper. The unpractical features of such a method of insulating are, of course, evident. The use of thin

\* See "Report of Progress in Warm-Air Furnace Research." Univ. of Ill. Eng. Exp. Sta., Bul. 112, 1919.

Coefficient of Emissivity- <i>K</i> B.t.u. per sq.ft. per hr. per 1°F.								Relative Efficiency Per Cent	Drum Number
0	0.2	0.4	0.6	0.8	1.0	1.2	1.4		
0.70	188.5	27							
2.20	60.0	28							
2.08	63.5	29							
0.90	146.5	30							
1.12	117.8	31							

## ONE HUNDRED AND SEVENTY TESTS ON STEAM DRUMS

layers of asbestos paper on bright tin pipes should be abandoned if the best results are to be obtained in furnace heating.

Values of the coefficients of emissivity *K* are given in the charts (Figs. 43a, 43b, and 43c). To use these data for the determination of the approximate heat loss from a pipe, it is necessary to multiply the value of *K* for the surface in question by the surface area of the

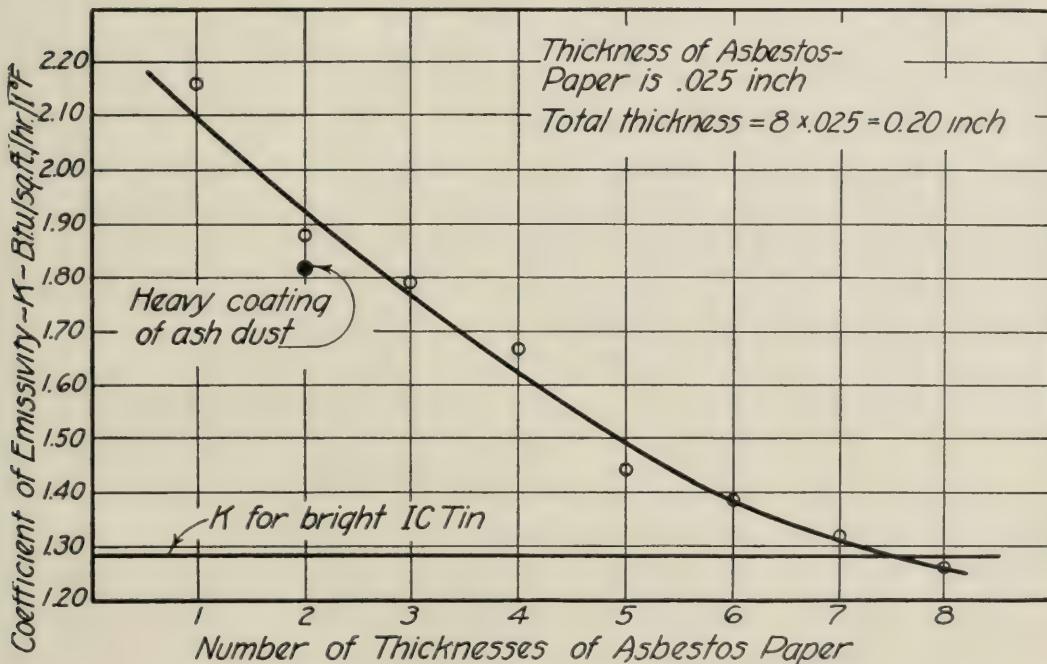


FIG. 44. INEFFECTIVENESS OF COMMERCIAL ASBESTOS PAPER FOR INSULATION ON BRIGHT TIN PIPE

pipe exposed, and then multiply by the difference between the temperature of the *surface* of the pipe,  $t_1$ , and that of the air outside the pipe,  $t_a$ , or,

$$\text{B.t.u. loss per hour} = K \times \text{Area in sq. ft.} \times (t_1 - t_a)$$

The results of the steam drum tests have been corroborated by results obtained on other apparatus.\*

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\* See "Emissivity of Heat from Various Surfaces." Univ. of Ill. Eng. Exp. Sta., Bul. 117, 1920.

## XII. HEATING SURFACE

43. *Heating Air by Hot Surfaces.*—When a hot surface is surrounded by cooler air, the surface loses heat in three ways, namely: by conduction, by convection and by radiation. Each particle of air in contact with the surface becomes warmed, and transmits some of this heat to the next particle of air with which it is in contact. This in turn transmits the heat to the next particle farther out, and if the air remains at rest relative to the surface, the whole mass of air will ultimately become warmed. This process is known as conduction. Air is a poor conductor of heat and if it is moving over the surface, very little of it, except the layers just next the surface, become heated by this method.

For the purpose of heating air, the process called convection is by far the most effective. In this process the particles of air touching the surface become heated and then move out into the cooler mass of air which is not touching the surface. At the same time they are replaced by particles which come from the cool mass of air and take their place touching the surface. In other words, currents are set up in the mass of air, and these currents constantly bring the cool particles of air into contact with the surface, where they are heated by contact. The amount of heat received in this manner is limited only by the rapidity with which the air can be kept in circulation and fresh portions of it brought into actual contact with the hot surface. For this reason surfaces so arranged that the air must impinge upon them are more effective than those surfaces over which the air must move parallel to the surface. In the latter case the air becomes stratified and heat can reach the outer layers by conduction only, and conduction is not very effective.

A hot surface constantly emits heat rays in just the same manner as a luminous surface emits light rays. The heat rays obey laws similar to those for light rays. This process is called radiation. The invisible heat rays travel in straight lines, and pass directly through dry air without warming it. If these rays, however, strike some body which is not transparent to them, they warm the body. The addition of water vapor to the air renders it slightly less transparent to radia-

tion, and humid air will be slightly warmed in this way. At the relative humidities found in warm-air furnaces, this effect is very small and may be disregarded. The amount of heat given off by radiation is dependent on the temperature and the nature of the surface. Dull surfaces, like cast-iron, will emit much more heat than bright ones, like polished nickel or tin. The emissivity of different surfaces has been discussed in Section XI. According to the Stefan-Boltzman law the amount of heat received by radiation varies directly as the difference between the fourth powers of the temperatures of the radiating body and the body receiving the radiation, and inversely as the square of the distance between the two bodies. This is true only for black bodies.

In the warm-air furnace, the heat given off from the castings by radiation is a total loss unless it can be saved by indirect methods. This may be done by interposing a shield in such a way that it receives the radiation and becomes warmed. The air may then be made to pass over this shield, coming in contact with it and in turn taking the heat from it by convection and conduction. The furnace casing serves to intercept part of the radiant heat and to give this heat back to the air. An additional saving can be made, however, by placing another shield inside of the casing and around the fire-pot. From the preceding discussion it will be evident that this shield will be most effective if it is made of some material like black iron and placed as near the hottest portions of the castings as is practicable.

Equipment has been installed to investigate the value of such shields, but no report can be made on this subject at present.

**44. Temperature of Heating Surfaces.**—The method used for the determination of the temperature of the metal of the castings for the pipeless furnace, together with the location of the thermocouples has been given in Section VI. (See Fig. 25.) The results of the work on the temperature of castings are by no means complete, but certain relations appear to exist and are discussed in the following paragraphs. The results were obtained from two sets of tests on hard coal, one with the slots in the fire-pot closed and one with the slots open. Two tests with soft coal, one with slots open, and one with slots closed were also run. The first tests show that for a given temperature-rise for the air passing through the furnace the fire-pot temperature is approximately 70 degrees higher when the slots are closed than when

they are open. This indicates that the air taken in through the slots materially cools the fire-pot. The results of preliminary tests on soft coal indicate that the temperature of the fire-pot for a soft coal fuel bed is about 200 deg. F. lower than for a hard coal bed. Much more work must be done on the temperatures for soft coal fires before rigid conclusions may be drawn, but the few tests run seem to justify this conclusion.

The tests so far completed also show that the mean temperature of the radiator for the hard coal fuel beds with closed slots in the fire-pot is approximately 37 degrees higher than it is with the slots open. Relatively, the decrease in temperature of the fire-pot with the addition of air through the slots is greater than the decrease for the radiator, which seems to indicate that with the introduction of air over the fuel bed the combustion in the zone above the fuel bed is increased and this tends to increase the temperature of the radiator. For the soft coal tests, the radiator temperature as a whole was not very different from that for the hard coal tests, and therefore about the same temperature difference was observed in the radiator temperatures with the slots in the fire-pot closed and open respectively.

The results further indicate that, for a given temperature-rise in the air passing through the furnace, with a hard coal fire the temperature of the castings, as a whole, is higher for a fire-pot with the slots closed than for one with the slots open. It is also evident that the temperature of the castings is higher for a hard coal fire than for a soft coal fire. The relation existing between fire-pots with slots open and with slots closed for hard coal fires holds also for soft coal fires. For any particular furnace, and for a given temperature-rise, all other conditions remaining the same, the castings will therefore give off a greater amount of heat in a unit time for a hard coal fire and a fire-pot with the slots closed than they will for a hard coal fire and a fire-pot with the slots open, or for soft coal fires under any conditions. The higher temperature with hard coal will cause greater radiation of heat which, of course, will be lost unless surfaces are interposed for the purpose of intercepting it, and the air is caused to pass over these surfaces to collect the heat.

This increased radiation loss does not account for all the additional heat available due to the higher temperature of the castings. Hence the air circulated must receive part of the additional heat. If the temperature-rise is the same in both cases, the only possible

way for the air to carry more heat in the case of a higher fire-pot temperature is for a greater weight of air to be circulated. A greater capacity is therefore to be expected from a hard coal fire, and an unslotted fire-pot, than from the slotted fire-pot, or from soft coal fires. That this is true may be shown by a study of Table 7.

In this table, the capacities for pipeless tests 10, 11, and 12, run under the conditions indicated, have been listed. At the corresponding temperature-rise, or equivalent register temperature, for each test, the capacity taken from the performance curves of Section IV has been listed. The performance curves were obtained when the furnace was operated with a hard coal fire and a fire-pot with the slots closed. In each case it may be seen that the capacity is less for the fire-pot with the slots open and for the soft coal fire than for the hard coal fire and the fire-pot with the slots closed.

The ratio of the mean temperature of the radiator to the mean temperature of the fire-pot is also given. As the temperature of the fire-pot decreases the capacity also decreases. It may also be seen that the capacity decreases as the ratio increases. This ratio apparently increases when increased combustion occurs above the fuel bed, as it does when air is admitted above the fuel bed or for the soft coal fires. In the soft coal fires more combustion takes place above the fuel bed than for hard coal fires, due to the larger volume of volatile combustible given off from the soft coal. This raises the zone of the mean temperature of the air between the air at the bottom of the furnace and at the register face. The weight of air circulated is a function of the difference between this mean temperature and

TABLE 7  
EFFECT OF CHARACTER OF COMBUSTION UPON FURNACE CAPACITY

Test No.	Date	Coal	Slots in Pot	Temperature-Rise	Equivalent Register Temperature above 65°	Capacity B.t.u. per Hour	Ratio of Mean Temperature of Radiator to Mean Temperature of Fire-Pot
From curve 10	1-28-21	Hard	Closed	138.6	203.6	121 000	0.672
		Hard	Open	138.6	203.6	110 500	0.703
From curve 11	1-31-21	Hard	Closed	139.5	204.5	122 000	0.672
		Soft	Closed	139.5	204.5	115 900	0.825
From curve 12	2-3-21	Hard	Closed	140.1	205.1	123 000	0.673
		Soft	Open	140.1	205.1	109 000	0.934

the temperature of the air outside the furnace casing, and of the effective heights of the warm air columns inside and outside the casing. Since the temperature-rise has been assumed constant for all this discussion, the difference between the mean temperature inside and outside the casing must also remain constant. Therefore the factor affected must be the effective height of the air columns causing the flow, and apparently raising the height of the zone of mean temperature within the casing must have the effect of shortening the effective height of the air columns and thus of reducing capacity.

From Table 7 may be gained some idea of the relative value of the heating surface. When combustion takes place higher up in the furnace the temperature of the upper surfaces is increased but relatively the temperature of the lower surfaces is decreased to a greater extent as indicated by an increase in the ratio given in the table. The net result is a decrease in capacity. It therefore appears that the value of the lower surfaces is much greater, and that every attempt should be made to have the air arrive at the bottom of the inner casing as cool as possible, to have the lower heating surfaces arranged as effectively as possible, and also to prevent their being cooled so that the air may receive its heat at as low a plane in the furnace as is practicable. Any attempt to prevent the radiation loss at this point by the interposition of extra surfaces to receive the radiation and to give back this heat to the air coming in contact with them will be effective, if the internal frictional resistance of the furnace is not materially increased by the additional surfaces.

The surfaces which are heated by contact with the burning fuel or by the burning gases above the fuel bed are known as primary heating surfaces. The surfaces which are interposed to be heated by intercepting radiation and in turn give this heat to the air by contact are known as secondary heating surfaces. At present no work has been done to determine the relative value of the two types of surfaces. The primary surface can also be divided into direct and indirect surfaces; the former includes any surface on which the fire "shines," while the latter includes those surfaces which are heated only by the flue gases. These indirect surfaces do not "see" the fuel bed at any point.

In Fig. 45 is given a curve showing the relation between the temperature difference between the flue gas and the air at the register face of the pipeless furnace, and the temperature difference between

the flue gas and the temperature of the metal in the radiator. In Fig. 46 is given a similar curve showing the relation between the temperature difference between the flue gas and the air, and the total drop in temperature of the metal in the radiator from the point at the center of the dome to the point where the gases leave the furnace. These curves serve to visualize the fact that the temperature difference between the flue gas and the temperature of the metal in the radiator is from 100 deg. F. to 350 deg. F. and that the total drop in the temperature of the metal of the radiator is from 225 deg. F. to 275 deg. F.

*45. Effect of Increasing Velocity of Air over Heating Surface.*—Results in practice indicate that the efficiency of the heating surfaces may be increased, and the capacity of a furnace materially raised, by the use of a fan to give positive circulation of air over the surfaces. The question of how much air can be forced over the heating surfaces of a given furnace before it begins to blow through the system without receiving much heat has been a source of considerable speculation. It is proposed to investigate this whole problem by the use of a fan in the recirculating duct of a piped furnace. In the meantime, in order to arrive at some preliminary conclusions

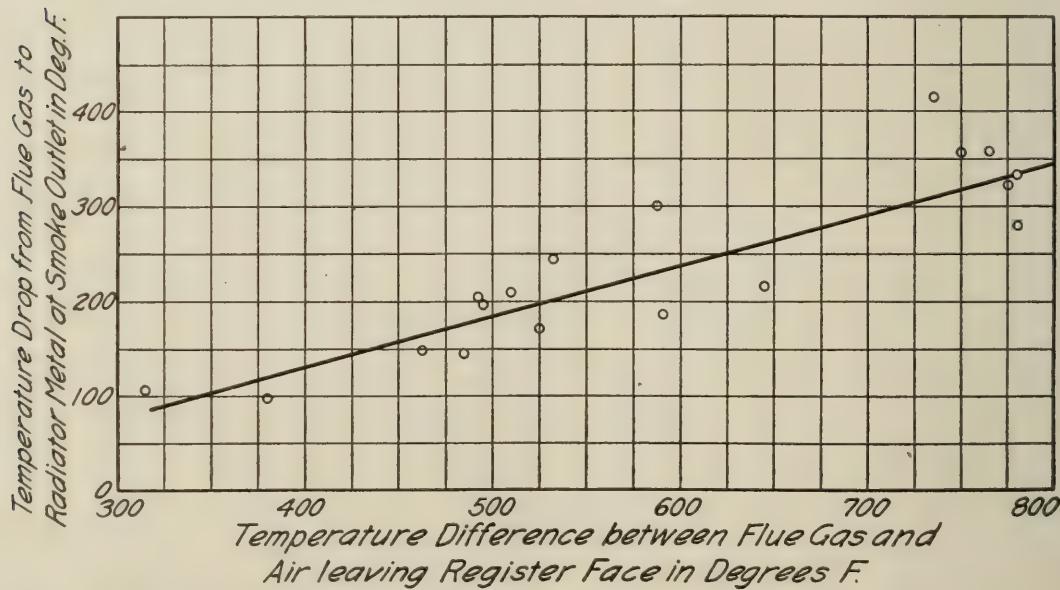


FIG. 45. RELATION BETWEEN THE FALL IN TEMPERATURE FROM FLUE GAS TO AIR CIRCULATED, AND FROM FLUE GAS TO METAL IN THE RADIATOR FOR A PIPELESS FURNACE

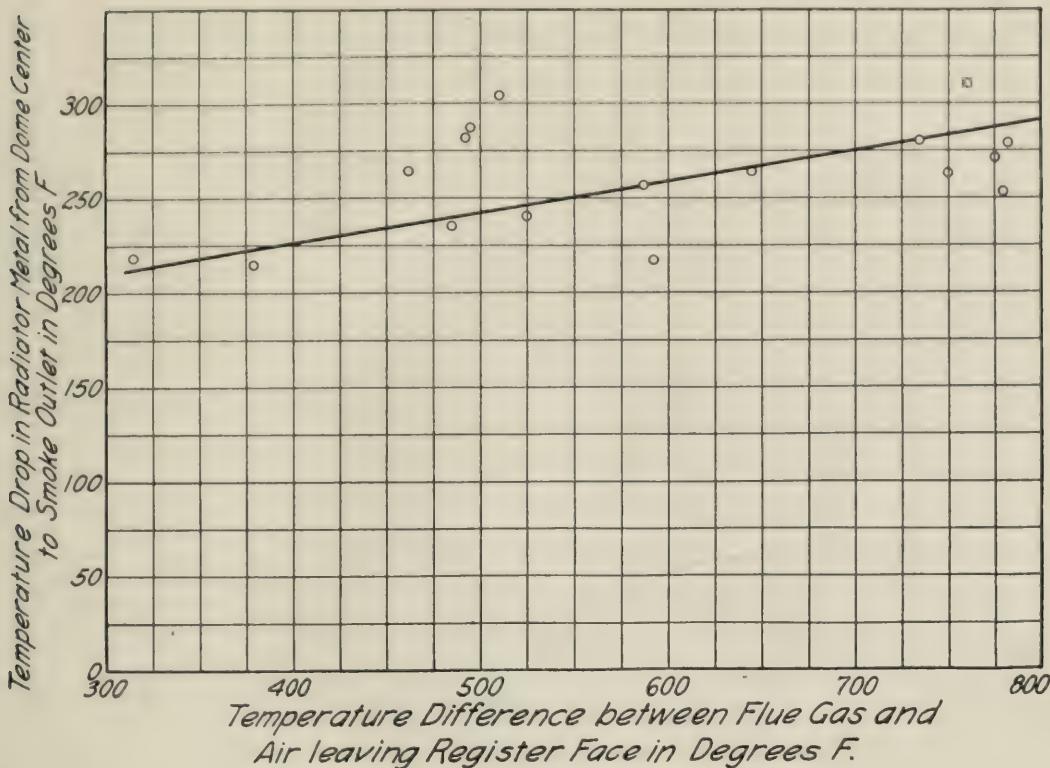


FIG. 46. RELATION BETWEEN THE FALL IN TEMPERATURE FROM FLUE GAS TO AIR CIRCULATED, AND THE FALL IN TEMPERATURE OF THE METAL FROM THE CENTER OF THE DOME TO THE GAS OUTLET FOR A PIPELESS FURNACE

in regard to this question, a few tests have been run, making use of the calibrating plant for the pipeless furnace for forcing the air through this furnace. The air was delivered into the outer casing at a point above the bottom of the inner casing so that short-circuiting was reduced as much as possible. A special plate was clamped down on the cold-air register face in the same manner as when the plant was used for calibrating. The velocity of the air at the warm-air register face was measured with an anemometer. In making an observation for any given velocity, the fan speed was held constant and observations were made of the temperature at the register face. When this temperature had become constant, readings were taken for a period of 30 minutes or more to insure that the temperature remained constant. At the same time traverses were made with the anemometer. From the readings taken during the 30 minutes the weight of air and the capacity of the furnace in B.t.u. were calculated. In Fig. 47 the capacities of the furnace in pounds of air per hour

when operating on the forced circulation and when operating on the natural circulation, respectively, are plotted against equivalent register temperature based on 65 deg. F. inlet. The limit of the fan was reached at a capacity of 10 200 pounds of air per hour. At this capacity it was possible to maintain an equivalent register temperature of 196 deg. F. The capacity of the furnace when operating on its own natural circulation at this register temperature was 3650 pounds of air per hour. It has therefore been possible to increase the capacity, in pounds of air per hour, 2.8 times and still to maintain a register temperature comparable with the usual register temperatures for pipeless furnace work.

In Fig. 48 the capacities in B.t.u per hour put into the air are shown for both natural and forced circulation. At an equivalent register temperature of 196 deg. F., it was found possible to force the furnace to a capacity of 328 000 B.t.u. per hour, and to maintain the register temperature. The corresponding capacity under natural circulation was 114 000. It was therefore possible to increase the

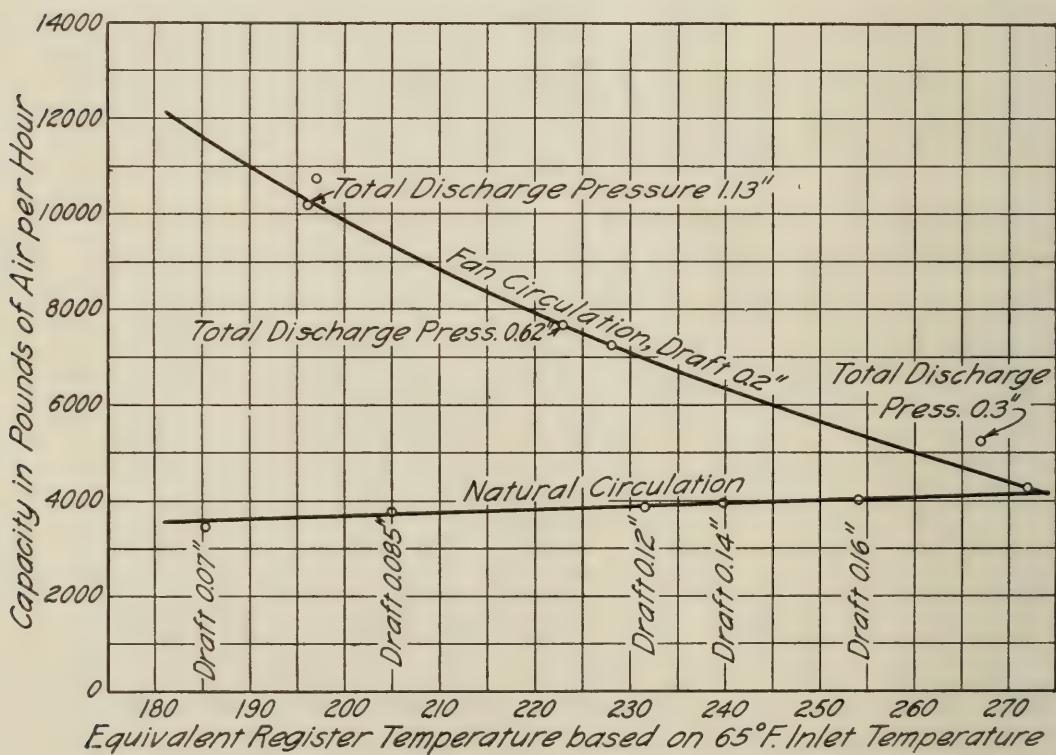


FIG. 47. EFFECT OF FORCED CIRCULATION ON THE CAPACITY IN POUNDS OF AIR PER HOUR FOR A PIPELESS FURNACE

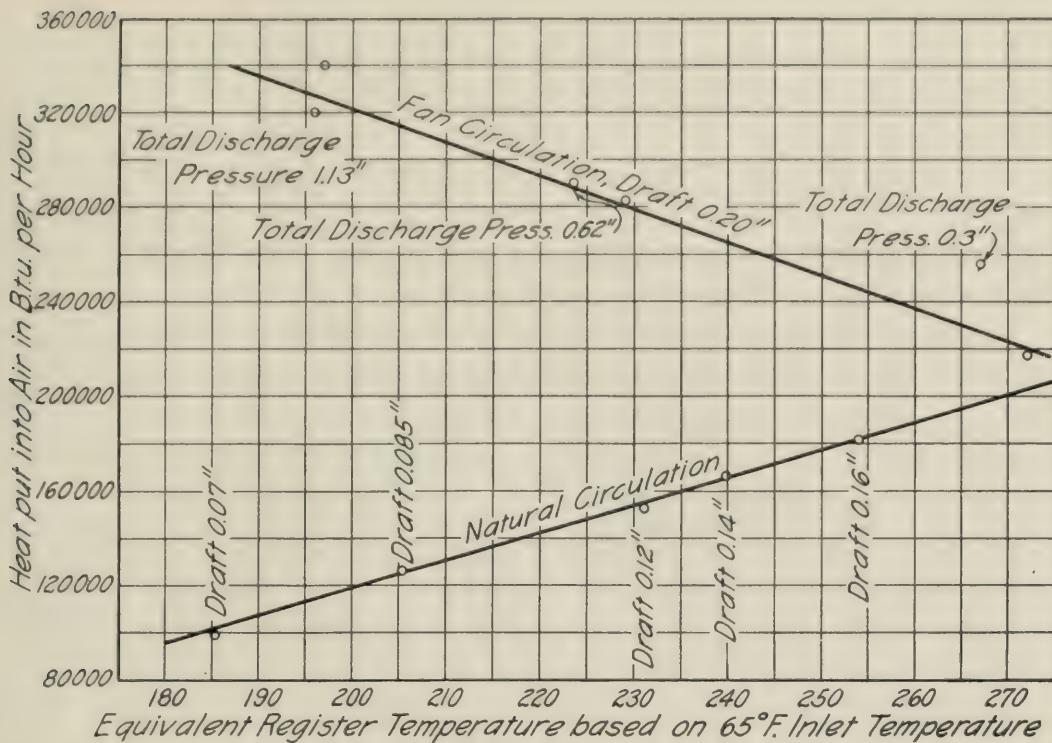


FIG. 48. EFFECT OF FORCED CIRCULATION ON THE CAPACITY IN B.T.U. PER HOUR TRANSFERRED TO AIR FOR A PIPELESS FURNACE

capacity in B.t.u. 2.88 times. On natural circulation it was possible to increase the capacity from 114 000 to 204 000 B.t.u. by an increase in register temperature of 77 degrees; this is an increase of 1.8 times. By using a fan and positive circulation it seems possible to increase the capacity of a pipeless furnace to from 2 to 3 times the capacity on natural circulation. It is doubtful, however, whether this could be done without objectionable noise. These experiments are preliminary to the investigation of the whole question of applying fans to warm air furnaces.

46. *Comparison of Fire-Pots with Open and with Closed Slots Respectively.*—In Fig. 49 the performance of the pipeless furnace with the slots in the fire-pot open and with soft coal has been compared with the normal performance obtained with a hard coal fuel bed and a fire-pot with slots closed. All these tests were run with an equivalent register temperature of approximately 204 deg. F., and are therefore comparable. In the case of the hard coal fire with the slots in the fire-pot open, the capacity and efficiency were very materi-

ally reduced. This was due to the large amount of excess air drawn in through the slots. Under normal operation with the slots closed, the weight of flue gas per pound of coal was about 13.0 lb., while in this test it was 21.9 lb. The difference was due to excess air. In order to handle this excess the furnace required a draft of 0.17 inches of water, which was far in excess of the 0.10 inches required normally. This establishes the fact that the use of a slotted fire-pot is detrimental in the case of hard coal fires.

The advantages or disadvantages of the open slots for soft coal fires are not established. In order to do this it will be necessary to run a number of tests under both conditions; the performance curves may then be directly compared. At present the comparison with the hard coal performance curves is of doubtful value, due to the fact that the shape of the soft coal curves is probably different. If an efficiency curve is drawn through the point representing the efficiency for test No. 12, a soft coal test with slots in the fire pot open, paralleling the efficiency curve for the hard coal fire with the slots closed, it may be seen that the point representing the efficiency on test No. 11, a

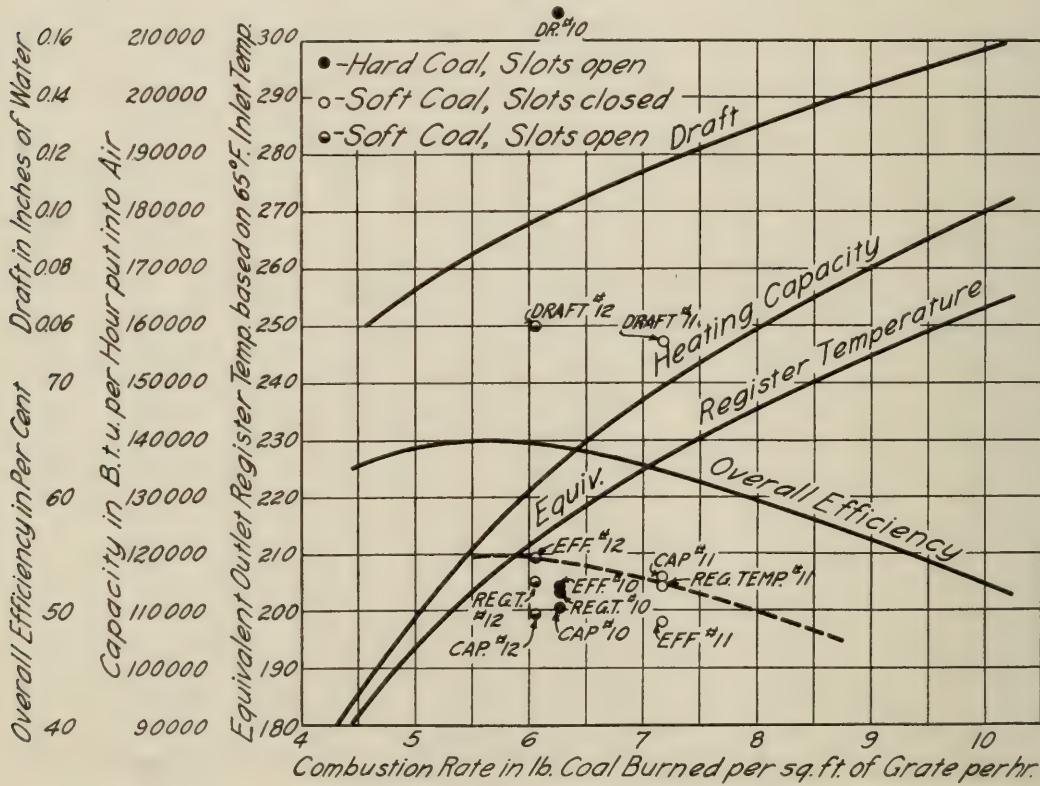


FIG. 49. COMPARISON OF FIRE-POTS WITH OPEN AND WITH CLOSED SLOTS RESPECTIVELY

soft coal test with the slots closed, falls below the curve so drawn, indicating that opening the slots has proved beneficial. This procedure is rather doubtful, however, due to the fact that the soft coal curves may not have the same shape as the hard coal curves, as already suggested. A study of the flue gas samples, however, indicated that for test No. 12, with the slots open, the excess oxygen in the gas was practically the same right after firing as it was at the end of an hour and just previous to the next firing. This indicates that the volatile was constantly distilling from the fuel bed, and that it required the air furnished through the slots at all times. Otherwise, as the coal coked and the volatile distilled became less, the gas samples would have shown more excess oxygen just previous to firing. From this standpoint the effect of the slots seemed to be beneficial.

Further corroborative evidence in favor of the conclusion that the open slots were to some extent beneficial may be found from the fact that the "unaccounted for" loss given in item 64 in the results under Section IV was 32 per cent for test No. 11, in which the slots were closed, while it was but 22.9 per cent for test No. 12, in which the slots were open. The latter value compares very favorably with the hard coal tests for which the average "unaccounted for" was approximately 18 per cent. The 10 per cent excess for test No. 11 may be attributed to loss due to volatile hydrocarbons escaping unburned in the flue gas. The addition of air over the fuel bed completed the combustion of these hydrocarbons in test No. 12.

These tests, however, were run under conditions which were most favorable to showing the slotted fire-pot to an advantage. For reasons stated under Section V it was found desirable to fire the coal in small amounts hourly. In this way the volatile was constantly being distilled from the fuel bed. Since it is only during the distillation period that additional air is required above the fuel bed, it is evident that extension of the distillation period over the whole firing period made the constant addition of air above the fire necessary. This air, of course, was supplied through the slots. If a large charge of coal had been fired and then allowed to coke, the slots would probably not have been so effective, since the air delivered by them after the distillation period, during the time the coke was being burned, would have been in excess of that required and would have tended to reduce the efficiency. This is somewhat speculative, however, and no rigid conclusions can be drawn until further work has been done in this field.

WARM AIR FURNACE RESEARCH ENGINEERING EXPERIMENT STATION UNIVERSITY OF ILLINOIS												
Results of Tests on Auxiliary Plant with 5 Types of Stack.												
Note: 10" x 10' Leader, 18' to Register, no Insulations used.												
INST. NO.	TIME No. Date	Regs. Inlet Temp. °F.	Inlet Temp. °F.	Diff. Regs. above 65°F	Equiv. Temp. Drop in Leader	Temp. Drop in Stack	Temp. Drop in Bonnet	%Btu Loss in Bonnet	%Btu Loss in Stack	%Btu Loss put into Stack-Air per Hour		
1	4-25-19	149.7	72.5	77.1	142.1	5.26	10.43	15.70	5.67	11.25	16.92	19050
2	5-26-19	165.75	84.9	80.8	145.8	5.67	10.08	15.75	5.86	10.53	16.39	19450
3	5-8-19	149.0	69.8	79.2	144.2	8.43	12.07	20.50	8.45	12.10	20.55	18100
4	5-31-19	164.28	84.6	79.7	144.7	7.25	10.04	17.30	7.48	10.37	17.85	18540
5	7-21-19	161.85	85.9	76.0	141.0	17.48	30.90	49.35	14.10	24.80	38.90	19900
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19	4-25-19	149.7	90.9	14300	71.0	201	5.50	73.8	78.54	100		
20	5-26-19	165.75	89.0	13700	6.87	242	5.41	88.6	78.54	100		
21	5-8-19	149.0	79.9	11960	600	179	4.72	70.1	78.54	100		
22	5-31-19	164.28	84.8	13900	6.98	227	5.18	86.5	57.00	72.5		
23	7-21-19	161.85	71.2	11900	5.97	186	4.30	89.7	39.00	50		
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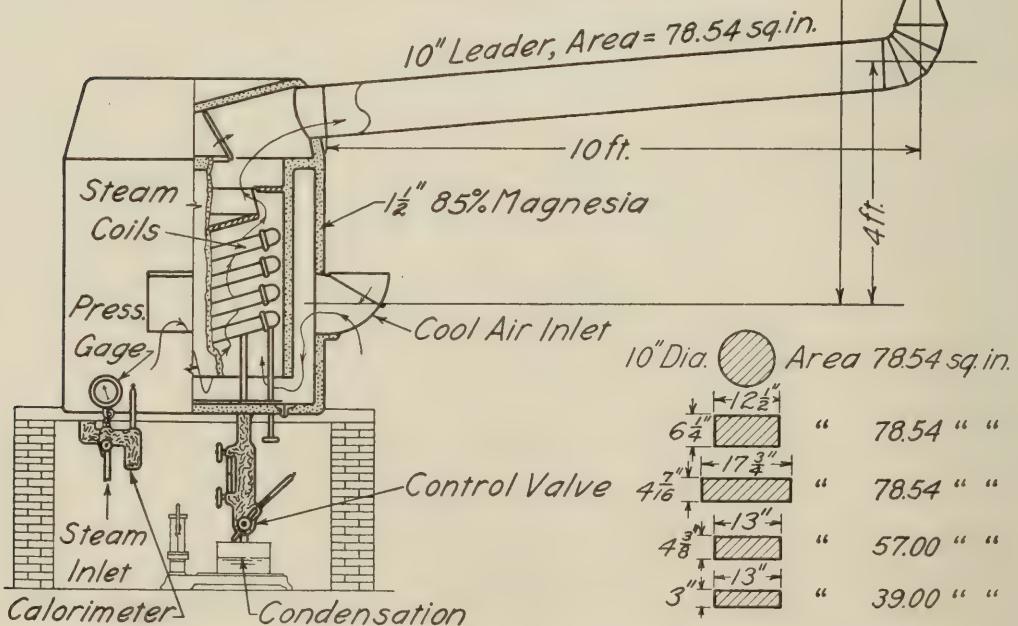
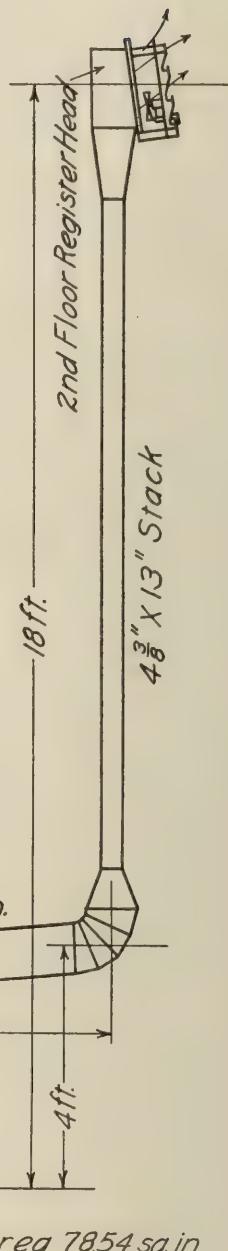


FIG. 50. SECTIONAL ELEVATION OF SINGLE LEADER PLANT FOR TESTING STACKS

### XIII. AUXILIARY PLANTS FOR TESTING LEADERS, STACKS, AND REGISTERS

47. *Proportions for Leaders and Stacks.*—The auxiliary equipment used in tests of leaders, stacks, and registers, included the single leader furnace, the register grille plant, and the pipeless furnace plant. The single leader plant has been described in detail in former publications.\* The elevation (Fig. 50) shows the arrangement of the plant. The particular problem was the determination of the relative air-handling capacities of stacks of various cross sectional areas and shapes. Five stacks were tested and the dimensions of their sections are given in the figure. The method of testing consisted of connecting each leader, in turn, to the boot at the end of the 10 inch by 10 foot leader pipe and running tests over a range of furnace temperatures and velocities. The velocities were measured at the register face in accordance with the standard method employed in all the furnace tests, by means of a calibrated anemometer. These velocities were used to calculate the weight of air flowing through the free area of the register. The temperature difference between register and inlet air was maintained in all cases at approximately 79 deg. F.

Table 8, following, furnishes data on the results of the tests.

TABLE 8  
SUMMARY OF DATA ON TESTS OF FIVE STACKS

Test No.	Stack Dimensions	Shape or Ratio of Sides	Area Sq. In.	Relative Area Stack to Leader Per Cent	Relative Air Capacity Leader and Stack Compared to Test No. 1 Per Cent
1	10 in. dia. round	Round	78	100	100
2	12½ in. wide 6½ in. deep	2 to 1	78	100	94
3	17¾ in. wide 4½ in. deep	4 to 1	78	100	93
4	13 in. wide 4¾ in. deep	3 to 1	57	73	90
5	13 in. wide 3 in. deep	4½ to 1	39	50	74

\* See Bulletins 112 and 117, Univ. of Ill. Eng. Exp. Sta., 1919, 1920.

The last two columns of the table contain the significant data. A stack of narrow cross section of 4 to 1 proportions had only 93 per cent of the air-handling capacity of the round stack although both were of equal area. However, a stack of 73 per cent relative area showed 90 per cent relative air-handling capacity, and a reduction to 50 per cent area only lowered the capacity to 74 per cent. These data indicate that stack capacity is dependent upon both the relative area and the shape of the stack cross section.

48. *Losses in Register Grilles.*—A special plant for testing register faces to determine the frictional loss through the grilles for a number of sizes and relative free areas of registers has been constructed, and preliminary tests have been made, but no final data are available for this report.

On the pipeless furnace plant, a test was made to determine the effect of grilles upon furnace capacity. Data for this test are given in Table 1, tests Nos. 7 and 9. The tests were made on a duplex cast-iron register 40 inches by 40 inches outside. The outlet register grille was of the removable type and had a discharge throat  $29\frac{3}{8}$  inches in diameter. A bar carrying the center bearing for the anemometer carriage extended across the open discharge outlet and reduced the area from 4.72 square feet to 4.65 square feet. Careful measurement of the openings in the grille showed a total free area of 2.83 square feet. Thus the percentage of free area of the register grille was  $100 \times 2.83 / 4.72$ , or 60.8 percent; this is a comparatively low percentage.

The method of testing consisted in running two tests at a fixed air temperature-rise through the furnace, but varying conditions by removing the register grille in one case. By calibrating the anemometer against the Wahlen gage and Pitot tube over both the open and the grilles faces the loss in air-handling capacity was readily determined. The calibration curves for the anemometer were plotted, as shown in Fig. 13, and then the average anemometer reading for each test was referred to the curves, and the difference in the weights of air ascertained. In comparing the weights of air taken from the curves, it was necessary to make slight corrections because of the fact that the temperature-rise through the furnace in the two tests was not the same. This correction was made in the calculation for the weight of the air as determined by the Pitot tube, and its amount appears in Table 9, which contains the complete results. Tests at

only one velocity of discharge, 6 ft. per second, were made, but the results were considered accurate for any ordinary range of register velocities.

Comparing the corrected weights of air as given in the table, it is evident that the per cent loss due to the grille was

$$\frac{3855 - 3740}{3855} \times 100 = 2.7,$$

which was the percentage loss in weight or volume of air flowing through the furnace. The heating capacity of the furnace operating with a grille of 60.8 per cent free area was correspondingly reduced. See tests Nos. 7 and 9, Table 1.

This loss proved so small that it has been concluded that losses due to grilles in pipeless furnaces are not important factors in furnace design. This statement *does not mean* that correct proportions between cold-air inlet area and warm-air outlet areas are of no consequence. It only means that in the typical pipeless furnace the actual free area of the hot air grille is not of great importance unless made less than 60 per cent of the outlet register opening.

TABLE 9  
RESULTS OF REGISTER GRILLE LOSS TESTS

Test No.		1	2
Face		Grille	Open
Temperature-rise in furnace	140.2	137	29.35
Barometer	29.08		
Weight of air corresponding to anemometer reading of 240	3740	3840	
Correction due to temperature difference	1.00	1.002	
Weight air per hour, lb., corrected	3740	3855	
Air at register temperature, lb. per cu. ft.	.0570	.0575	
Volume of air handled cu. ft.	65 600	67 000	
Free area, sq. ft.	2.83	4.65	

Ratio of free areas =  $\frac{2.83}{4.65} \times 100 = 60.8$  per cent.

## APPENDIX

THE ORGANIZATION OF THE FURNACE RESEARCH STAFF AND THE  
ADVISORY COMMITTEE

The agreement between the University and the Association provides for a staff of at least two full-time research associates and one half-time research assistant, who shall be under the direction and supervision of the Engineering Experiment Station. The agreement also provides for an Advisory Committee on Furnace Research appointed by the President of the Association. This committee meets in conference with the Furnace Research Staff, as occasion may demand, for the consideration of new subjects to be listed in the program of investigation, a review of the work accomplished, and a discussion of any matters affecting the scope of the investigation.

It has been found very difficult to assemble and maintain a complete research staff for carrying on this work. Changes in personnel are matters of serious consequence, as the loss of an experienced investigator in research work may mean a delay of months before a new man can become properly acquainted with the work, and develop the necessary testing technique to secure reliable test data.

The personnel of the research staff from the time the investigation was started in October, 1918, to April 1, 1921, is given in the following:

## FURNACE RESEARCH STAFF

C. R. RICHARDS..... Dean College of Engineering, and Director  
Engineering Experiment Station.

A. C. WILLARD..... Professor Heating and Ventilation, and Head of  
Department of Mechanical Engineering.

A. P. KRATZ..... Research Assistant Professor.

S. L. SIMMERING\*.. Research Associate.

F. G. WAHLEN†.... Research Graduate Assistant.

V. S. DAY..... Research Assistant and later Research Associate.

W. E. PRATT\*..... Special Investigator and Research Associate.

C. Z. ROSECRANS†.... Research Graduate Assistant.

C. G. BRADLEY..... Mechanician (half-time).

\* Professor Simmering resigned March 31, 1919.

Mr. Pratt resigned December 1, 1919.

† Mr. Wahlen and Mr. Rosecrans are connected with the work only during vacation periods.

At the present time Professor Kratz and Mr. Day are devoting their full-time to this work; and they are assisted by Mr. Bradley, on half-time.

#### ADVISORY COMMITTEE ON FURNACE RESEARCH

The personnel of the Advisory Committee has been changed somewhat since the investigation was started<sup>‡</sup> and its present organization is given in the following:

P. J. DOUGHERTY, Chairman, Heating Engineer, International Heater Co., Utica, N. Y.

E. S. MONCRIEF, Vice President, Henry Furnace and Foundry Co., Cleveland, Ohio.

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<sup>‡</sup> "Report of Progress in Warm-Air Furnace Research." Univ. of Ill. Eng. Exp. Sta., Bul. 112, pp. 57-58, 1919.



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